(1) F° 104088 RR FR

PCT WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : H01S 3/06 | A1

(11) International Publication Number: WO 98/25326

(43) International Publication Date: 11 June 1998 (11.06.98)

(21) International Application Number: PCT/GB97/03353

(22) International Filing Date: 4 December 1997 (04.12.97)

(30) Priority Data:
9625231.7 4 December 1996 (04.12.96) GB

(71) Applicant (*for all designated States except US*): UNIVERSITY OF SOUTHAMPTON [GB/GB]; Highfield, Southampton, Hampshire SO17 1BJ (GB).

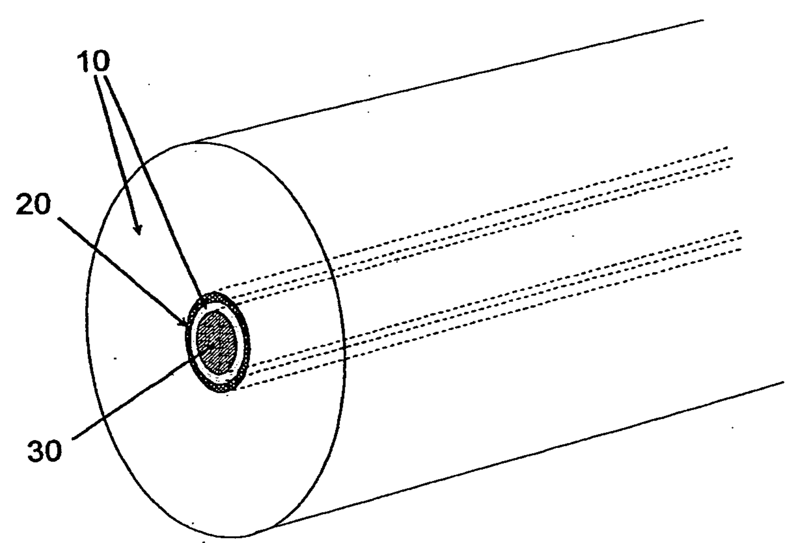
(72) Inventors; and
(75) Inventors/Applicants (*for US only*): NILSON, Johan [SE/KR]; Samsung 1–cha Apt. 2–701, Kyungki–do, Paldal–gu, Maetan–4 dong, Suwon 442–374 (KR). HANNA, David, Colin [GB/GB]; 246 Hill Lane, Shirley, Southampton, Hampshire SO15 7PH (GB). MINELLY, John, Douglas [GB/GB]; 21 Tremona Court, Tremona Road, Shirley, Southampton, Hampshire SO16 6TH (GB). PASCHOTTA, Ruediger, Eberhard [DE/CH]; Benedikt–Fontana–Weg 17, CH–8049 Zürich (CH).

(74) Agent: TURNER, James, Arthur; D. Young & Co., 21 New Fetter Lane, London EC4A 1DA (US).

(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ARIPO patent (GH, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: OPTICAL AMPLIFIER AND LIGHT SOURCE



(57) Abstract

We disclose single– or few–moded waveguiding cladding–pumped lasers, superfluorescent sources, and amplifiers, as well as lasers, including those for high–energy pulses, in which the interaction between the waveguided light and a gain medium is substantially reduced. This leads to decreased losses of guided desired light as well as to decreased losses through emission of undesired light, compared to devices of the prior art. Furthermore, also cross–talk and inter–symbol interference in semiconductor amplifiers can be reduced. We also disclose devices with a predetermined saturation power. As a preferred embodiment of the invention, we disclose a single (transverse) mode optical fibre laser or amplifier in which the active medium (providing gain or saturable absorption) is of the fibre's cross section where the intensity of the signal light is substantially reduced compared to its peak value. The fibre may be cladding–pumped.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece			TR	Turkey
BG	Bulgaria	HU	Hungary	ML	Mali	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MN	Mongolia	UA	Ukraine
BR	Brazil	IL	Israel	MR	Mauritania	UG	Uganda
BY	Belarus	IS	Iceland	MW	Malawi	US	United States of America
CA	Canada	IT	Italy	MX	Mexico	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NE	Niger	VN	Viet Nam
CG	Congo	KE	Kenya	NL	Netherlands	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NO	Norway	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	NZ	New Zealand		
CM	Cameroon			PL	Poland		
CN	China	KR	Republic of Korea	PT	Portugal		
CU	Cuba	KZ	Kazakstan	RO	Romania		
CZ	Czech Republic	LC	Saint Lucia	RU	Russian Federation		
DE	Germany	LI	Liechtenstein	SD	Sudan		
DK	Denmark	LK	Sri Lanka	SE	Sweden		
EE	Estonia	LR	Liberia	SG	Singapore		

OPTICAL AMPLIFIER AND LIGHT SOURCE

The invention relates to optical amplifiers and light sources. By way of example, though not exclusively, the invention relates to single- or few-moded waveguiding lasers, superfluorescent sources, optical amplifiers, high pulse-energy devices, energy-storage devices, cladding-pumped devices, semiconductor signal amplifiers, and waveguiding saturable absorbers.

The tightly confined modal fields of single- or few-moded waveguiding lasers, superfluorescent sources, and amplifiers lead to a very strong interaction between any waveguided light and the active medium in the waveguiding core. Therefore, a comparatively small amount of gain medium is sufficient for providing the gain in these devices. Specifically, the gain for a given stored energy, as well as for a given absorbed pump power, is high. This is often beneficial, since it means that the pump power requirements for a given desired laser output power or amplifier gain can be low.

However, for several devices, this efficient interaction between mode and gain medium can be detrimental. The follwowing example refers to certain types of amplifiers and lasers, but of course the skilled man will realise that the same or similar problems can occur in, for example, superfluorescent sources.

In a laser or amplifier, the achievable single-pass gain is limited to, say, 50 dB. The reason is that at this gain, a significant fraction of the pump power is converted to amplified spontaneous emission (ASE). A 10 dB higher gain results in approximately 10 dB more ASE, so at these gains, the extra pump power required to increase the gain further will be prohibitively high. Since the ASE limits the gain of the device, it also limits the energy stored in the gain medium. This in turn obviously limits the amount of energy that a pulse can extract from the device. Consequently, the pulse energy that can be obtained from waveguiding lasers and amplifiers is limited. Instead, bulk (i.e., not waveguiding) lasers and amplifiers for which the extractable energy for a given gain can be several orders of magnitude lower are often employed to provide much higher pulse energies. However, the robustness and stability of bulk lasers is often inferior to waveguiding ones.

Moreover, the gain limit can also be problematic for lasers and amplifiers irrespective of whether the stored energy is a major concern, if the high gain appears at another wavelength than the desired one. The reason is that ASE (or lasing) at the gain peak will suppress the gain achievable at the desired wavelength, possibly to a value below what is required for a good amplifier or laser. This applies to all types of amplifiers and lasers.

Furthermore, in optically pumped lasers and amplifiers, a suitable interaction between the gain medium and the amplified or generated signal beam is not enough; also the interaction between the pump beam and the gain medium must be appropriate. However, in some types of lasers and amplifiers (typically cladding-pumped ones), the interaction with the pump beam is significantly smaller than the interaction with the signal beam. Then, for a device that efficiently absorbs the pump, the interaction with the signal beam will be much stronger than is required. Unfortunately, this excess interaction is often accompanied by excess losses for the signal beam, since:

1. The scattering loss of an active medium is normally higher than it can be for a passive medium. For instance, rare-earth-doped fibres have scattering losses of, e.g., several orders of magnitude higher than standard, passive, single-mode fibres.
2. A fraction of the active medium often has inferior properties. For instance, in Er-doped fibres, pairs of Er^{3+}-ions may form. These result in an unbleachable loss. The strong interaction then leads to a high loss.
3. The active medium in its amplifying state may also absorb light (so-called excited-state absorption, ESA). Again, a stronger interaction leads to more power lost through ESA.

Moreover, a bleachable medium (e.g., an unpumped gain medium with a ground-state absorption) can be used as a saturable absorber. An efficient interaction leads to a low saturation power. A reduced interaction leads to a higher saturation power, which may be more suitable for some applications, especially if the interaction, and hence the saturation power, can be controlled.

Clearly, although often beneficial, the tight confinement of the guided light is a problem for some devices.

Various aspects of the invention are defined in the appended claims, and in passages throughout the present application.

Embodiments of the invention provide devices that are considerably improved by a predetermined reduction of the interaction between a signal light beam and an active medium (per unit volume) compared to prior art designs, without necessarily changing the properties of the gain medium or reducing the confinement of the signal light (although a reduced confinement can also be beneficial for the disclosed devices). The active medium serves to amplify or generate the signal light beam, or, if unpumped, can act as a saturable absorber.

The reduction in interaction is achieved by placing the bulk of the active medium in regions where the intensity of the signal beam is substantially smaller than its peak intensity, in a cross-section of the waveguiding device perpendicular to the direction of propagation of the signal beam. This can provide advantages for the following devices:

1. Lasers (e.g., Q-switched and gain-switched ones) and amplifiers in which it is desirable to store large energies. In these devices (as well as for so-called energy-storage devices in general), the reduced interaction leads to a larger stored energy before practical upper limits on the gain is reached.
2. Optical amplifiers (typically semiconductor ones) for which even the energy of a single signal bit may be comparable to the stored energy. In those, already the amplification of a bit extracts enough energy to reduce the gain. This leads to four-wave mixing, cross-talk, and inter-symbol interference. This can be reduced with the higher stored energy that, for a given gain, accompanies the reduced interaction.
3. Amplifiers and lasers in which an efficient pump absorption necessitates large amounts of gain media, which in prior-art devices leads to excessive small-signal absorption, background absorption, or excited state absorption at the operating wavelength, or excessive gain at another wavelength. A reduced interaction then leads to reduced losses. Moreover, a reduced interaction can reduce the gain at the undesired wavelength relative to that at the desired one, and thereby the problems associated with a too high gain at wrong wavelength. This applies to lasers in which there is a significant unpumped loss

(typically, reabsorption loss or out-coupling loss). These points are especially relevant for cladding-pumped devices. For example, to ensure sufficient pump absorption, the fibre may need to be so long that one or both of those problems arise.

4. Saturable absorbers, in which the saturation power is otherwise too small.

Embodiments of the invention can overcome or alleviate some of the problems described above and can at least partially achieve one or more of the following:

1. To reduce the susceptibility to so-called quenching and background losses, in particular for cladding-pumped devices.
2. To obtain efficient emission at wavelengths otherwise inaccessible for devices where there is a significant unpumped loss, in particular for cladding-pumped devices.
3. To improve the energy storage capabilities, for energy-storage devices.
4. To reduce signal cross-talk and inter-symbol interference for signal amplifiers.
5. To allow for a larger, predetermined, saturation power.

Embodiments of the invention can provide the following devices and embodiments, and the use of the following amplifying and/or absorbing waveguiding structures in such devices:

1. An amplifying optical fibre in which the active medium is placed partly or wholly outside the waveguiding core, e.g., in a ring around the core. The gain medium may also reside inside the core in regions where the normalized modal intensity of the signal beam is small. The fibre may be made of a glass, partly doped with Pr^{3+}, Tm^{3+}, Sm^{3+}, Ho^{3+}, Nd^{3+}, Er^{3+}, or Yb^{3+}, or a combination thereof, and it may be cladding-pumped.
2. A cladding-pumped amplifier or laser in which the difference between the overlaps of the pump and signal beams with gain medium is substantially reduced compared to prior-art designs.
3. A ring-doped optical fibre for high-energy pulse amplification or generation or other energy storage applications. The fibre may for instance be made of a glass, partly doped with Pr^{3+}, Tm^{3+}, Sm^{3+}, Ho^{3+}, Nd^{3+}, Er^{3+}, or Yb^{3+}, or a combination thereof, and it may be cladding-pumped. Moreover, the device may incorporate a longitudinally distributed

saturable absorber to suppress the build-up of ASE. In one embodiment, the gain medium is a Yb^{3+}-sensitized Er^{3+}-doped glass, and the saturable absorber is an Er^{3+}-doped glass, and they are located so that the signal intensity is higher in the saturable absorber than in the gain medium.

4. A Q-switched or gain-switched fibre laser based on an amplifying fibre with a relatively higher saturation energy combined with a saturable absorber fibre having a relatively lower saturation energy. The difference in saturation energy stems, at least to a significant part, from differences in the geometry of the fibres. The active media in the different fibres may be the same or different, and may for instance be a glass doped with a rare earth, e.g., Pr^{3+}, Tm^{3+}, Sm^{3+}, Ho^{3+}, Nd^{3+}, Er^{3+}, or Yb^{3+}, or a combination thereof.
5. A ring-doped, cladding-pumped ytterbium-doped fibre for amplification or generation of light in the range 950 nm to 1050 nm.
6. A ring-doped, cladding-pumped neodymium-doped fibre for amplification or generation of light in the range 850 nm to 950 nm.
7. A ring-doped, cladding-pumped erbium-doped fibre for amplification or generation of light in the range 1450 nm to 1600 nm.
8. An amplifying planar waveguide structure in which the active medium is placed partly or wholly outside the waveguiding core, thus interacting with the signal beam only where the normalized intensity of the modal field is small. The waveguide may be cladding-pumped. Moreover, the design may be specifically adapted to correspond to any of the fibre devices listed above.
9. A semiconductor amplifier for signal amplification, in which the gain region is placed partly or wholly outside the waveguiding core, thus interacting with the signal beams only where their normalized modal intensities are small. Thereby, the saturation energy of the device will be increased, which subsequently reduces the inter-symbol interference and inter-wavelength cross-talk.

10. A waveguiding structure with a saturable absorption, in which the absorbing medium is placed partly or wholly outside the waveguiding core, thus interacting with the signal beam only where its normalized modal intensity is small.

Evanescent-field devices, including ring-doped fibre devices have not been considered for devices of the type proposed here, nor has any device been proposed or demonstrated based on ring-doping (or evanescent-field interaction) that provide significant benefits of the type considered here, compared to traditional devices in which the gain-medium resides in the core in places where the interaction with the signal beam is large. Specific differences between embodiments of the invention and a prior art device are as follows:

1. It has not been one of the specific devices considered here.
2. It has not used a single-moded or few-moded waveguiding core.
3. It has not been a device in which the energy extraction results in cross-talk or inter-symbol interference.
4. The control of the emission wavelength that we propose has not been obtained.
5. The device has not substantially reduced the effect of losses at the signal wavelength.
6. It has not been a cladding-pumped device.
7. It has not been a device for high-energy pulses.
8. It has not been an optical fibre doped with erbium or another rare-earth for high-energy pulses.
9. The output of the device could not be launched into a standard single-mode fibre through splicing or butt-coupling, nor has the device allowed for an easy launch of signal light.
10. The output beam has not been tightly confined.
11. It has been a device doped in regions of the core where the modal intensity is large.
12. It has been a device doped in a large area around the core (e.g., homogeneously in the cladding), hence rendering it inefficient for cladding-pumping.
13. It has not been a fibre structure, or at least not an all-fibre structure.
14. It has not been a solid-state device.
15. The interaction length has been limited to a few centimeters.

16. It has not been a high-gain device.
17. It has not been a device pumped by an optical beam guided along the amplifying medium.
18. It has not been possible to manufacture the device with standard manufacturing techniques for rare-earth doped fibres like MCVD and solution doping.
19. The purpose of the design has not been to obtain a smaller interaction between the gain medium and the signal light than would otherwise be possible, nor have any substantial benefits of a substantially smaller interaction been proposed, discussed, or demonstrated.

The invention will now be described by way of example with reference to the accompanying drawings, throughout which like parts are referred to by like references, and in which:

Figure 1 illustrates a Ring-doped optical fibre;

Figure 2 illustrates the dependencies of the refractive index, the gain medium, and the modal field across a transverse cross-section through the centre of the fibre in Figure 1;

Figure 3 illustrates a planar waveguide structure amplifying the evanescent field of a signal beam;

Figure 4 illustrates a double-clad ring-doped optical fibre;

Figures 5a and 5b illustrate examples of the proposed devices;

Figure 6 illustrates the extractable energy and small-signal gain at 1550 nm for a ring-doped erbium-doped fibre (EDF) pumped by 0.1 W, 0.2 W, and 0.5 W at 1480 nm in the core;

Figure 7 illustrates the extractable energy and small-signal gain at 1550 nm for a ring-doped erbium-doped fibre (EDF) pumped by 0.1 W, 0.2 W, and 0.5 W at 980 nm in the core;

Figure 8 illustrates the normalized modal intensity Ψ *vs*. ring position for the ring-doped EDFs of Figs. 6, 7, and 10.

Figure 9 illustrates the extractable energy ("pulse energy above cw") vs. launched pump power for a core-pumped fibre amplifier with an Yb^{3+}-doped ring;

Figure 10 illustrates the extractable energy and small-signal gain at 1550 nm for a ring-doped EDF cladding-pumped by 1 W and 5 W at 980 nm;

Figure 11 illustrates a view of a fibre having a saturable absorber in the central part of the core and a ring-shaped gain medium around the absorber;

Figure 12 illustrates a semiconductor amplifier for signal amplification; and

Figures 13a to 13c illustrates devices in which unwanted, higher-order modes are suppressed by the inclusion of an absorber.

Figure 1 depicts a ring-doped optical fibre. A transparent cladding (10) (typical radius 50 μm – 250 μm) surrounds a transparent waveguiding core (30) of a higher refractive index, with a diameter of typically a few to ten μm (micrometres). The core is surrounded by a gain medium (20), which can amplify a signal beam, guided by the core. The gain medium may be pumped by an optical pump beam, which may also be guided by the core.

In this example, the gain medium is formed of the same glass as the remainder of the cladding, except that the glass in that region is doped with a dopant providing gain properties. However, different materials could be used for the cladding and the gain medium. The gain region is a generally cylindrical region surrounding the core.

Figure 2 illustrates the normalized modal intensity distribution Ψ, the refractive index profile with the core (30), and the dopant profile (20), in a transverse cross-section through the center of the fibre. For an optical fibre in glass, the cladding refractive index is typically around 1.5, and the numerical aperture is typically around 0.1 – 0.3.

Figure 3 shows a waveguiding amplifier or laser. As for the fibre, a transparent cladding (110) surrounds a transparent waveguiding core (130) of a higher refractive index. A gain medium (120) (e.g. formed by doping the cladding glass or as a separate medium) is situated near the core.

Figure 4 is similar to Fig. 1, except that the inner cladding (10) is now surrounded by an outer cladding (210), of a lower refractive index. Thus, the inner cladding can guide light, and serves to guide a pump beam launched into the inner cladding. The signal beam is guided by the core (30).

Figures 5a and 5b illustrate examples of an erbium-doped fibre amplifier and a fibre laser respectively. For the amplifier of Figure 5a, a signal beam in an optical fibre is launched

into a wavelength-selective coupler (310). Also an optical pump beam from the pig-tailed pump source (320) is launched into the coupler, which combines the pump and signal beams and launches them both into an erbium-doped fibre (330). In the fibre, the erbium-ions serve to transfer energy from the pump beam to the signal beam, which is thereby amplified. The amplified signal is then, for example, launched into another fibre for further transmission.

For the laser of Figure 5b, a beam from an optical pump source (370) is coupled via a lens (350) into a fibre (340) doped with a gain medium. The ends of the fibre provide some means (360) for reflecting a signal beam, possibly with wavelength discrimination, thus providing feedback for the laser oscillator. The reflector at the pump input end transmits the pump and reflects the signal, while the out-coupling reflector in the other end transmits a significant fraction of the signal beam. Other components are also often used in the devices of Figures 5a and 5b, e.g. an isolator for the amplifier; however those have been omitted for clarity.

Although it is clear that the ideas and concepts disclosed below apply to many different geometries, the discussion below will for conciseness be focused on ring-doped fibres. Moreover, it will be assumed that the structures are longitudinally uniform, although this is not necessarily so.

Other waveguiding geometries can also be used. For example, the core may be of a more complicated shape than the traditional ones illustrated in the drawings. The invention also extends to cores that fulfill the same or a similar function as traditional ones do, and allow for an active medium to be incorporated in a region where the normalized modal intensity is small.

Moreover, while the embodiments primarily deal with devices pumped by an optical beam propagating along the core, other pumping schemes are also possible, like flash-lamp pumping and side-pumping with diode bars, electrical pumping, chemical pumping, and more.

While advantages are described of localizing the active medium in regions where the normalized modal field is small, the active medium may also extend to regions where it is

large. Even in cases when this significantly alters the characteristics of a device, the invention covers also these devices as long as the benefits of the designs disclosed here remain to some degree.

Principle

The disclosed devices provide advantages compared to prior-art, core-doped, ones by suppressing gain and thus radiation losses at undesired wavelengths and/or by reducing the propagation losses in the device. Below follows a description of how these advantages are obtained. We restrict the discussion to homogeneously broadened gain media; substantial benefits can be realized also in inhomogeneously broadened ones. The description focuses on cladding-pumped devices.

It is known that with a gain medium for which the shape of the gain spectrum depends on the population inversion, the emission wavelength of a fibre can be modified by changing the strength of the interaction between a signal beam and the gain medium. For instance, the fibre length can be changed. This also changes the absorption of the pump. However, we will demonstrate below that in cladding-pumped devices, the same control can be obtained through ring-doping, while separately controlling the absorption of the pump. In particular, the pump absorption can be kept sufficiently large, as will be further described in the following.

The following relation can be used for evaluating the gain G in a waveguiding device with a homogeneously broadened gain medium [1]:

$$G = \frac{10}{\ln 10}[\sigma^e \iint N_0(x,y)n_2(x,y)\Psi(x,y)\mathrm{d}x\mathrm{d}y - \sigma^a \iint N_0(x,y)(1-n_2(x,y))\Psi(x,y)\mathrm{d}x\mathrm{d}y]L \quad \text{[dB]} \qquad (1)$$

where N_0 is the concentration of amplifying centra, n_2 is the degree of excitation, Ψ is the normalized mode intensity, σ^a and σ^e are the absorption and emission cross-section of the active centra, respectively, and L is the length of the gain region. Equation 1 can be written in a simplified form:

$$G = (10 / \ln 10)\, N_0\, A_{doped}\, \Psi_{doped}\, [n_2\, \sigma^e - (1 - n_2)\, \sigma^a]\, L \quad \text{[dB]} \qquad (2)$$

where N_0, n_2, and Ψ_{doped} have been appropriately averaged over the doped area A_{doped}. (In the literature, the product $A_{doped}\,\Psi_{doped}$ is often replaced by the so-called overlap Γ.)

There are two assumptions in Eqs. 1 and 2, namely, that the gain is homogeneously broadened and that only two levels in the gain medium are significantly populated. However, even for devices that do not meet these assumptions, the problems that we address exist and can generally be countered by designing devices according to our present invention. In the notation, there is also the implicit, unimportant, assumption that the gain stems from a number of active centra, each of which has been ascribed cross-sections for stimulated emission and absorption. Other types of gain media also exist, and the results will be valid also or them. To proceed, we will also assume that the degree of inversion is wavelength-independent. This is normally true to a good approximation. If not, this results in a slight inhomogeneity in the gain spectrum. For simplicity, we have also assumed that other losses are small compared to either the gain G or the bleachable absorption $(10/\ln 10)N_0 A_{doped}\Psi_{doped}\sigma^a L$. Again, this is a non-restrictive assumption, and the equations can be easily modified to include any other loss. For instance, a filter can be used for controlling the gain spectrum and laser output wavelength, both in prior-art devices and the devices disclosed here.

It follows from Eq. 2 that the gains G_1, G_2, and G_3 at three different wavelengths λ_1, λ_2, and λ_3 are related to each other in the following way:

$$G_3 = G_2\,(\Psi_{3,\,doped}/\Psi_{2,\,doped})\,(\sigma_3^e/\sigma_1^e - \sigma_3^a/\sigma_1^a)\,/\,(\sigma_2^e/\sigma_1^e - \sigma_2^a/\sigma_1^a)$$
$$+\,G_1\,(\Psi_{3,\,doped}/\Psi_{1,\,doped})\,(\sigma_3^e/\sigma_2^e - \sigma_3^a/\sigma_2^a)\,/\,(\sigma_1^e/\sigma_2^e - \sigma_1^a/\sigma_2^a) \qquad \text{[dB]} \qquad (3)$$

Equation 3 makes the important point that for given cross-sections, the only parameters that affect this relation are the normalized mode intensities, averaged over the doped region. Let now λ_1 be the pump wavelength. The pump is then absorbed by an amount $\alpha_p^{operating} \equiv -G_1$ in the operating state of the device. In order to operate efficiently, $\alpha_p^{operating}$ needs to be sufficiently large, say, at least 5 dB. Also, we assume that we require a certain gain G_2 at a wavelength λ_2. $\alpha_p^{operating}$ and G_2 are then parameters already specified. This also implies a certain gain G_3 at other wavelengths λ_3, but if this gain is too large, prohibitive amounts of power will be lost to ASE. Insofar as the cross-sections cannot be significantly modified, this can only be remedied by designing the device for appropriate values of the

normalized modal intensities. The description of such designs is a central part of the present invention.

To simplify the further description, we now assume that the pump does not stimulate any emission; hence, $\sigma_1^e = 0$. Equation 3 then becomes

$$G_3 = G_2\,(\sigma_3^e\,\Psi_{3,\,doped} / \sigma_2^e\,\Psi_{2,\,doped}) + \alpha_p^{operating}\,(\sigma_3^e\,\Psi_{3,\,doped} / \sigma_p^a\,\Psi_{p,\,doped})\,[(\sigma_2^a/\sigma_2^e) - (\sigma_3^a/\sigma_3^e)] \quad \text{[dB]} \qquad (4)$$

The value of the first term depends on the relative sizes of $\Psi_{2,\,doped}$ and $\Psi_{3,\,doped}$ at λ_2 and λ_3. In a fibre, the spot-sizes at λ_2 and λ_3 may differ. Then, ring-doping implies that the gain at the wavelength with the larger spot-size gets relatively larger than at the other wavelength, compared to a homogeneously doped core. Depending on how close the wavelengths are to each other, this is often not a significant effect.

In contrast, in cladding-pumped devices, the second term in Eq. 4 can to a significant extent be controlled by designing the device for an appropriate value of $(\Psi_{3,\,doped} / \Psi_{p,\,doped})$. Normally, it is very different in a cladding-pumped device and in a core-pumped device. In the core, the normalized pump intensity Ψ_p is approximately equal to the inverse of the pumped area for both core-pumped and cladding-pumped devices, so the same is true for $\Psi_{p,\,doped}$ in a core-doped device. It follows that in a core-doped device, $\Psi_{p,\,doped}$ will be much larger in a core-pumped device than in a cladding-pumped device. Thus, the *effective area ratio* $r_{effective} \equiv (\Psi_{3,\,doped} / \Psi_{p,\,doped})$ will be much larger. (We will also use "effective area ratio" for the ratio $\Psi_{2,\,doped} / \Psi_{p,\,doped}$.) Consequently, a core design which is suitable for the core-pumped device may be inappropriate for a cladding-pumped device because the effective area ratio becomes too large. In prior-art cladding-pumped devices, $r_{effective}$ is large, typically around 100. Then, the second term in Eq. 4 is potentially large for some undesired wavelength λ_3, which makes it difficult to absorb the pump without getting a high gain at the undesired wavelength. Therefore, laser systems with significant reabsorption that work well in a core-doped, core-pumped, geometry will not be efficient core-doped, cladding-pumped lasers. (In a device doped in the core, $r_{effective}$ is approximately equal to the *area ratio*

$r \equiv A_{pumped} / A_{doped}$, where A_{pumped} is the pumped area and A_{doped} is the doped area. Hence, for a cladding-pumped device homogeneously doped throughout the core, $r = A_{cladding} / A_{core}$.)

Consider instead a ring-doped, cladding-pumped device. Since Ψ_p is approximately constant over the inner cladding, $\Psi_{p,\,doped}$ will not change much with the transverse disposition of the gain medium. However, since the light at λ_3 is confined to the core, $\Psi_{3,\,doped}$ decreases rapidly if the amplifying region is moved away from the core. This obviously reduces the interaction between the gain medium and the signal beam. Hence, the devices disclosed here allows $r_{effective}$ to be substantially reduced, e.g., to values in the range $1 - 10$, whereby the gain at unwanted wavelengths can be suppressed compared to the gain at a desired wavelength.

First, we treat the case where the scattering (or absorption) loss of the gain region is larger than that of a transparent, passive region. For simplicity, we assume that there is no scattering loss outside the gain region. Starting from Eq. 2, we can then derive the following expression between the scattering loss and the gain G_1 and G_2 at two different wavelengths:

$$\alpha_2^{scatter} = \sigma_2^{scatter}\,[G_2\,(\sigma_1^{\,a} + \sigma_1^{\,e}) - (\Psi_{2,\,doped} / \Psi_{1,\,doped})\,G_1\,(\sigma_2^{\,a} + \sigma_2^{\,e})] \,/\, (\sigma_1^{\,a}\sigma_2^{\,e} - \sigma_1^{\,e}\sigma_2^{\,a}). \quad [\mathrm{dB}] \qquad (5)$$

In Eq. 5, we have arbitrarily made the non-restrictive assumption that each active center scatters with a cross-section $\sigma_2^{scatter}$. Also, we have for simplicity assumed that scattering is small compared to the gain. It follows that the scattering losses can become high already at a small value of the ratio between stimulated emission and scattering $(\sigma_2^{scatter}/\sigma_2^{\,e})$ if $r_{effective} \approx 100$, i.e., in a core-doped, cladding-pumped device. Then, already a value $(\sigma_2^{scatter}/\sigma_2^{\,e})$ as low as 1/1000 can result in significant losses. In contrast, in ring-doped cladding-pumped devices, acceptable values of $(\sigma_2^{scatter}/\sigma_2^{\,e})$ will be one or two orders of magnitude larger.

Next, we will show how ring-doping also can reduce the sensitivity to quenching. Very often, some active centra in a gain medium are defect. These quenched centra retain their ground-state absorption (GSA), but, if they absorb a photon, they are not efficiently excited. This leads to a so-called unsaturable absorption, the spectrum of which is

approximately proportional to the small-signal ground-state absorption spectrum of the medium. For instance, this type of unsaturable absorption has been observed in the important Yb^{3+}:glass and Er^{3+}:glass gain media. The small-signal absorption is given by:

$$\alpha_2^{ss} = \sigma_2^a \left[G_2 (\sigma_1^a + \sigma_1^e) - (\Psi_{2,doped} / \Psi_{1,doped}) G_1 (\sigma_2^a + \sigma_2^e)\right] / (\sigma_1^a\sigma_2^e - \sigma_1^e\sigma_2^a), \quad [\text{dB}] \qquad (6)$$

If, for instance, 3% of the active centra are quenched, we get an unsaturable absorption of $0.03\times\alpha 2ss$. Equation 6 is very similar to Eq. 5, and the same result holds: A cladding-pumped device with the currently disclosed design will be typically 10 – 100 times less sensitive to quenching than are core-doped designs of the prior-art. (This does not apply to four-level systems, for which $\alpha 2ss = 0$ dB.)

Next, we consider the case of excited-state absorption at the signal wavelength λ_2. Again, a stronger interaction leads to more power lost through ESA, at least for a device with significant small-signal absorption, as the following equations will show. The excited-state absorption can be written as

$$\alpha_2^{ESA} = \sigma_2^{ESA} \left[G_2 / \sigma_2^a - (\Psi_{2,doped} / \Psi_{1,doped}) G_1 / \sigma_1^a\right] / \left[(\sigma_2^e - \sigma_2^{ESA})/\sigma_2^a - \sigma_1^e/\sigma_1^a\right] \quad [\text{dB}] \qquad (7)$$

For a transition to the ground-state, the total excited-state absorption can be significant already for values of $\sigma_2^{ESA}/(\sigma_2^e - \sigma_2^{ESA})$ of 1/1000. Again, in cladding-pumped devices, the sensitivity can be reduced one or two order of magnitudes by ring-doping. (For four-level transitions, $\sigma_2^a = 0$, so the sensitivity to ESA is independent of any ring-doping, and equal to that of traditional core-doped, core-pumped devices.)

Equations 1 – 7 thus demonstrate how ring-doping makes the disclosed devices less susceptible to absorption loss and scattering losses and to emission losses to ASE at an undesired, high-gain wavelength. The improvements are a direct consequence of the reduction of the *effective* area ratio $r_{effective} \neq r$ to values around 1 – 10. In contrast, in prior-art devices, the signal light in the core is confined to an area approximately 100 times smaller than that of the pump, so the area ratios $r \approx r_{effective} \approx 100$. While the area ratio may well be made larger, a smaller area ratio is troublesome since a smaller area of the inner cladding can

make it difficult to launch the pump into the device, and since a larger signal spot-size leads either to a large bend sensitivity or to a multi-mode core.

In addition to the general designs described up to this point, we next describe some particular cladding-pumped fibre lasers and amplifiers with sizable advantages compared to the prior art.

Ytterbium-doped fibre operating in wavelengths between 975 and 985 nm

For Yb^{3+}-doped devices at these wavelengths, the suppression of quasi-four-level emission around 1030 nm can be especially troublesome for cladding-pumped devices designed according to the prior art. For a wavelength of 975 nm (corresponding to the peak of the cross-sections) with representative cross-section values (cf. Table A1), Eq. 3 gives the following relation between the gain at 975 nm, the gain at 1028 nm, and the pump absorption of the pumped (i.e., partly bleached) fibre:

$$G_{1028} = 0.25\, G_{975} + 0.74\, (\Psi_{doped} / \Psi_{p,\, doped})\, \alpha_p^{operating} \quad [\mathrm{dB}] \qquad (8)$$

Here, we have assumed that $\Psi_{975,\, doped} = \Psi_{1028,\, doped}$, which is a reasonable approximation for guided modes at nearby wavelengths. Now, assume that we want the laser to work at 975 nm, with 3.5% reflectivity at one end and 100% at the other one. Then, if the background losses are negligible, $G_{975} = 7.28$ dB. Consider first a representative core-doped prior-art design with $r \approx r_{effective} = 100$. Then, for every dB of pump absorption we get 74 dB of gain at 1028 nm. Since the gain at unwanted wavelengths must be below approximately 50 dB, we would have to restrict the single-pass pump absorption to below 1 dB or 20%. This would be a highly inefficient laser. Instead, we propose to use ring-doping. Then, the pump absorption can be 5 dB or more, which allows for a good laser efficiency. Note that increasing the end-face reflectivity at 975 nm will not help us much, as the high gain at 1028 nm largely follows from the requirements on pump absorption, while it is comparatively insensitive of the gain at 975 nm. For the same reason, the gain at 1028 nm will not be much higher for a high-gain amplifier at 975 nm than it is for a low-gain laser, so the disclosed design provides benefits for both applications.

A high-power laser at 975 nm can be used for pumping Er^{3+}. Also other wavelengths can be used for this, e.g., 980 nm and 985 nm. However, also those wavelengths are severely affected by unwanted emission around 1030 nm.

In the following, we will show that lasing at 975 nm will be particularly sensitive to any unbleachable Yb^{3+}, the existence of which has been reported in [2]. This sensitivity can be order of magnitudes higher in core-doped designs according to prior art, compared to the devices of the present invention.

From Eq. 6, we get

$$\alpha_{975}^{ss} = 1.07\, G_{975} + 6.48\, (\Psi_{doped} / \Psi_{p,\, doped})\, \alpha_p^{operating} \qquad \text{[dB]} \qquad (9)$$

Hence, with a prior-art design for cladding-pumping, we get several thousand decibels of small-signal absorption at 975 nm for a desired pump-absorption of around 5 dB. For $r_{effective} = 100$, already an unsaturable fraction of 1% of this (the lowest value reported in [2]) leads to an unsaturable absorption of around 30 dB, which is unacceptable. With the new devices, the sensitivity is drastically reduced. Even further reductions are possible by lasing at other wavelengths, e.g.,

$$\alpha_{980}^{ss} = 0.83\, G_{980} + 1.34\, (\Psi_{doped} / \Psi_{p,\, doped})\, \alpha_p^{operating} \qquad \text{[dB]} \qquad (10)$$

at 980 nm, and

$$\alpha_{985}^{ss} = 0.64\, G_{985} + 0.37\, (\Psi_{doped} / \Psi_{p,\, doped})\, \alpha_p^{operating} \qquad \text{[dB]} \qquad (11)$$

at 985 nm. The sensitivity to quenching is much reduced, and can be quite small in a ring-doped device.

While the analytic considerations above clearly demonstrate the advantages of the embodiments, they do not quantify the advantages in terms of the most important laser characteristics, namely, pump threshold P_{th} and slope efficiency η_{slope}. In order to provide a more complete description of the improvements compared to prior art, we next present calculations of P_{th} and η_{slope} from simulations with a spectrally and spatially resolved numerical model [3]. The only significant simplification in the model is that the pump is always assumed to be uniformly distributed across the inner cladding. Besides that, the gain medium is assumed to be homogeneously broadened, which is reasonable for Yb^{3+}:glass

systems. With the model, we analyzed fibres of different core-doped and ring-doped designs. In all cases, we kept the doped area constant, equal to the core size, while the outer radius r_d^{outer} of the doped area and hence Ψ_{doped} was varied. The area ratio was 80, and $\Psi_{p,\,doped} = (3080\ \mu m^2)^{-1}$. Other parameters are given in Table A2.

A first studied cavity had one laser mirror formed by a bare, cleaved, fibre end, providing a broadband reflectivity of 3.5%, while a narrow-band reflector (typically, a fibre bragg-grating) provided a 99.9% reflectivity in a desired laser wavelength range 975 nm to 977 nm. Outside this range, the reflectivity was zero, as can be achieved with an AR-coated or an angle-cleaved fibre end.

Lasing in the desired wavelength range was prevented by strong ASE at long wavelengths (1028 nm – 1035 nm) until r_d^{outer} became 5 μm. Then, the diameter of the inner ring is 4.2 μm and $r_{effective} = 5.8$ in good agreement with earlier estimates. The results are presented in Table 1.

r_d^{outer} / µm	r_d^{inner} / µm	$r_{effective}$	α^{ss} / dB/m	P_{th} / W	$\eta_{slope}\times 100$	$P_p^{transmitted}$
3.5 – 5	0 – 3.6	64 – 12	170 – 31	*No lasing for a pump power of 5 W. ASE around 1030 nm dominates the output*		22% – 46%
5.5	4.2	5.8	15.3	2.01±0.1	69±2	26%
6.0	4.9	2.9	7.47	2.14±0.1	66±2	29%
6.5	5.5	1.6	4.03	2.37±0.1	62±2	33%
7.0	6.1	1.0	2.58	2.78±0.1	61±2	34%
7.5	6.6	0.57	1.43	3.62±0.1	51±2	44%

Table 1. Laser characteristics of 10 m long unquenched fibre operating at 976 nm, with a HR fibre grating and a bare, cleaved end providing the laser cavity reflections. The small-signal absorption α^{ss} applies to a wavelength of 977 nm. The transmitted pump power $P_p^{transmitted}$ is expressed as a fraction of the launched pump power. r_d^{inner} is the inner radius of the gain medium.

Clearly, in contrast to prior-art devices, the device disclosed here can lase at 976 nm with a good efficiency. The range of acceptable effective area ratios is 1 – 6. The slope efficiency with respect to absorbed pump was approximately 93% – a quite high number which in reality will be lowered by background losses. These were assumed negligible in the calculations.

A shorter fibre length favors lasing at shorter wavelengths in a two-level system like this. However, shortening the fibre to 5 m is not sufficient for lasing at 976 nm in a core-doped design. Moreover, at this length, a significant fraction of the pump is not absorbed. Hence, making the fibre sufficiently short to ensure 976 nm lasing in a core-doped design is not an attractive option, even if the pump is double-passed through the cavity. The conclusion is that prior-art designs are inadequate for lasing at 976 nm for the considered area ratio.

Above, the smaller ring diameters appear to be better than the larger ones (provided that lasing is obtained). However, if a fraction of the Yb-ions are quenched, this will change, as is evident from Table 2.

r_d^{outer} / µm	r_d^{inner} / µm	$r_{effective}$	α^{ss} / dB/m	P_{th} / W	$\eta_{slope}\times 100$	$P_p^{transmitted}$
3.5 – 4.5	0 – 3.5	64 – 22	170 – 57	*No lasing for pump power of 10 W. ASE around 1030 nm dominates the output*		33% – 47%
5.0	3.5	12	30.6	1.69±0.1	29±2	50%
5.5	4.2	5.8	15.3	1.77±0.1	34±2	53%
6.0	4.9	2.9	7.47	2.04±0.1	33±2	58%
6.5	5.5	1.6	4.03	2.57±0.1	29±2	64%
7.0	6.1	1.0	2.58	3.58±0.1	26±2	68%

Table 2. Laser characteristics of 5 m long fibre operating at 976 nm, with 2% of the Yb^{3+}-ions quenched. A HR fibre grating and a bare, cleaved end provided the laser cavity reflections.

At 980 nm and 985 nm, the fibre behaved similarly as at 976 nm, except that 985 nm would not lase for an output reflectivity of 3.5%. A grating with 50% reflectivity at the output end allowed for lasing at 985 nm. In contrast, lasing at 976 nm in an unquenched fibre was only marginally improved by a grating also at the output end, and for a partly quenched fibre, results were worse with a grating than with a bare end. Also, as predicted in Eqs. 9–11, the longer wavelengths are less sensitive to quenching than are the 976 nm lasers.

These and other detailed numerical model calculations have shown:

- The earlier analytic considerations are largely accurate in determining whether or not a laser can work efficiently.
- The disclosed devices perform much better as lasers at 975 nm – 985 nm than do prior-art designs.

- The best value of the effective area ratio is around 3 –10 for this laser.
- The sensitivity to quenching is reduced with a smaller effective area ratio.
- The susceptibility to quenching is smaller at 980 nm and especially at 985 nm than it is at 976 nm.

Neodymium-doped fibre operating on the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition (850 nm – 950 nm)

A device designed in a similar way as the Yb^{3+}-doped cladding-pumped fibre will also improve on prior-art designs for this Nd^{3+}-transition. For Nd^{3+}-doped devices at these wavelengths, the suppression of the dominant $^4F_{3/2} \rightarrow {}^4I_{11/2}$ at 1050 nm transition is a problem, especially for cladding-pumped devices. For a wavelength of 870 nm, typical cross-sections (cf. Table A1) gives the following relation between the gains at 870 nm and around 1050 nm and the pump absorption of the pumped fibre:

$$G_{1050} = 3\ G_{870} + 1.5\ (\Psi_{doped} / \Psi_{p,\ doped})\ \alpha_p^{operating} \qquad \text{[dB]} \qquad (12).$$

The relations will be similar for other wavelengths in this transition. Equation 12 reveals that the gain at 1050 nm will be at least three times larger than that at 870 nm. This limits the 870 nm gain to 15 dB – a comparatively low but still useful number. However, with a prior-art, core-doped device, it will not be possible to absorb the pump properly, since the gain at 1050 nm becomes prohibitively high already for a single-pass pump absorption of less than 0.5 dB (≈ 10%). On the other hand, in a ring-doped device, $r_{effective}$ may be reduced by a factor 10 or more, so an absorption $\alpha_p^{operating}$ of at least 5 dB (= 68%) is possible, while still allowing for a single-pass gain at 870 nm of 10 dB.

In Eq. 12, we for simplicity assumed that Ψ_{doped} is equal at 1050 nm and 870 nm. However, for ring-doping, Ψ_{doped} will be larger at 1050 nm than at 870 nm. This means that the factor "3" in Eq. 12 actually will be larger. For instance, with a numerical aperture of 0.1 and a core diameter of 6 μm, a doped ring with $r_d^{inner} = 4$ μm and $r_d^{outer} = 5$ μm gives $(\Psi_{1050,\ doped} / \Psi_{870,\ doped}) = 1.6$. Then, $G_{1050} = 4.8\ G_{870} + 1.5\ (\Psi_{doped} / \Psi_{p,\ doped})\ \alpha_p^{operating}$. Nevertheless, appropriate designs allow enough gain for efficient lasing at 870 nm before the gain at 1050 nm becomes unrealistically large. The 870 nm gain can be even higher in modified designs: If the core has a higher cut-off wavelength of, e.g., 950 nm, the core will be

multi-moded at 870 nm. Since the higher-order LP_{11}-mode penetrates further into the cladding than the fundamental LP_{01}-mode does, the LP_{11}-mode gain at 870 nm is higher than the gain of the LP_{01}-mode. Hence, higher-order mode lasing at 870 nm becomes relatively easier to achieve compared to the 1050 nm lasing in the fundamental mode.

Erbium-doped fibre operating on the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition (1450 nm – 1600 nm)

The concerns of this device are similar to those of the cladding-pumped Yb-doped fibre described above. For instance, if we want the device to operate at 1531 nm, emission at 1564 nm or longer wavelengths is a potential problem in an aluminosilicate host. From Eq. 3 and Table A1, we get

$$G_{1564} = 0.6\, G_{1531} + 0.7\, (\Psi_{doped} / \Psi_{p.\,doped})\, \alpha_p^{operating} \qquad [\mathrm{dB}] \qquad (13)$$

Clustering is a well-known problem in erbium-doped fibres, and results in a saturable absorption. Equation 6 gives

$$\alpha_{1531}^{ss} = G_{1531} + 5\, (\Psi_{doped} / \Psi_{p.\,doped})\, \alpha_p^{operating} \qquad [\mathrm{dB}] \qquad (14)$$

These numbers are similar to the ones for Yb^{3+} operating at 976 nm, so ring-doping allows for similar improvements as for Yb^{3+}.

The wavelength range 1550 nm – 1565 nm is technologically important for optical communication systems. In this range, lasing at 1550 nm may be particularly hard to achieve, because the gain at, e.g., 1564 nm may become prohibitively large. From Eq. 3, we get

$$G_{1564} = 0.79\, G_{1550} + 0.15\, (\Psi_{doped} / \Psi_{p.\,doped})\, \alpha_p^{operating} \qquad [\mathrm{dB}] \qquad (15)$$

Also in this relatively benign case, adequate pump absorption can be troublesome in a prior-art design for unfavorable values of $r_{effective} \equiv (\Psi_{doped} / \Psi_{p.\,doped})$, so a ring-doped fibre will be advantageous. As it comes to the unsaturable absorption, we have that

$$\alpha_{1550}^{ss} = 0.6\, G_{1550} + 2.0\, (\Psi_{doped} / \Psi_{p.\,doped})\, \alpha_p^{operating} \qquad [\mathrm{dB}] \qquad (16)$$

Core-doped devices may then have an unsaturable absorption of 1000 dB, so a ring-doped fibre is better.

Principle

The type of high-energy pulse amplifiers and lasers we consider are so-called energy-storage devices in which a pulse extracts significant amounts of energy stored in the gain

medium. The energy supplied by the pump *during* the generation/amplification of a single pulse may be negligible. The amount of energy stored in the device then sets an upper limit on how much energy can be extracted by a pulse. This is a significant difference compared to other laser and amplifiers, for which power extraction is typically limited by the supplied pump power, and in any case not by the stored energy.

In order to obtain high-energy pulses from such an energy storage laser or an amplifier, we need both a large stored (and extractable) energy and a sufficiently high gain. While the gain efficiency of waveguiding amplifiers means that it is often easy to meet the second objective, the same gain efficiency can make it difficult to store large amounts of energy in the device: The gain efficiency implies that a comparatively small amount of extractable energy in the gain medium leads to a high gain. However, as already pointed out, since ASE limits the achievable gain of the device, it also limits the energy that can be stored [4].

The gain G in a transverse mode is related to the energy E stored in the gain medium through the following relation:

$$G = (10/\ln 10)\,[\Psi_{doped}E(\sigma^a + \sigma^e)/h\nu - \alpha L] = (10/\ln 10)\,[\Psi_{doped}E/U_{sat} - \alpha L] \quad [\mathrm{dB}] \qquad (17)$$

$$= (10/\ln 10)\,\Psi_{doped}\,E^{extractable}/U_{sat} = (10/\ln 10)\,E^{extractable}/E_{sat}$$

Here, $h\nu$ is a photon energy, αL is the unpumped loss of the medium, $U_{sat} \equiv h\nu/(\sigma^a + \sigma^a)$ is the saturation energy fluence, $E^{extractable}$ is the energy over the bleaching level, i.e., the maximum energy that can be extracted from the device, and $E_{sat} \equiv U_{sat}/\Psi_{doped}$ is the saturation energy. The important point is that G is proportional to Ψ_{doped}. Hence, a smaller value of Ψ_{doped} leads to a smaller gain per unit extractable energy. Therefore, for a gain medium located in a region where the normalized modal intensity of the signal beam is small, the extractable energy for a given gain will be high. Then, if the gain is sufficiently large for the device in question, a device with low values of Ψ_{doped} will be capable of generating or amplifying pulses to high energies.

Here, we disclose the use of devices that, although the light is tightly confined in a single- or few-moded waveguide, have a small value of Ψ_{doped} for high-energy pulse amplifiers and lasers, e.g. Q-switched and gain-switched ones. Note that any effect this may have on the relative gain at different wavelengths can be counteracted by simply making the device longer or increasing the concentration of active centra.

In addition to the general geometries described earlier, we will now describe some specific geometries and devices.

Core-pumped ring-doped pulse fibre amplifier or fibre laser

In the important class of core-pumped devices, the pump and the signal are guided by the same core. For instance, most erbium-doped fibre amplifiers (EDFAs) are of this type. Typically, the gain medium may be a Tm^{3+}, Sm^{3+}, Ho^{3+}, Nd^{3+}, Er^{3+}, or Yb^{3+}-doped glass. The desired weakness of the interaction between the signal beam and the gain medium normally then implies that also the interaction with the pump beam is weak, whereby the pumping of the medium becomes weaker and the pump absorption smaller. Nevertheless, the disclosed devices can show significant improvements.

We can distinguish two cases:

1. The pump and signal wavelengths are close, so the signal and pump mode profiles are close to each other. In this case, it is just a matter of finding suitable values of Ψ for placing the ring. These will depend on the lifetime and cross-sections of the dopant, the pump power and pulse energy, and other parameters. Figure 6 shows how the extractable energy and small-signal gain at 1550 nm depends on the position of the ring for a ring-doped EDF core-pumped by 0.1 W, 0.2 W, and 0.5 W at 1480 nm. Figure 6 illustrates the extractable energy and small-signal gain at 1550 nm for a ring-doped erbium-doped fiber (EDF) pumped by 0.1 W, 0.2 W, and 0.5 W at 1480 nm in the core. The ring thickness was sufficiently thin to make variations of the normalized intensity of the modal field negligible over its thickness. Other parameters are listed in Tables A3 and A4 under "normal-core amplifier". For comparison, also results for erbium-doped fiber amplifiers (EDFAs) homogeneously doped throughout the core are shown, both for the "normal-core" amplifier and a "large-core"

amplifier. In all cases, a higher pump power gives a higher small-signal gain and a larger extractable energy. Moreover, the fiber length was optimized for maximum small-signal gain in all cases. The advantages compared to the prior-art EDFs (also shown) are substantial. Figure 8 shows model calculation results on how Ψ_{doped} depends on the ring position for the ring-doped EDF. The method used for these and other similar calculations in this specification follows [4].

2. The pump and signal mode profiles are different. In this case, the pump is unlikely to penetrate far into the cladding, so the doped region must be inside the core or immediately outside the core. Unfortunately, for positions for which the signal intensity is suitable, the pump intensity tends to be much too weak. A good design should then aim at reducing this problem as far as possible. Figure 7 is similar to Fig. 6, except that the pump wavelength is now 980 nm. In particular, Figure 7 illustrates the extractable energy and small-signal gain at 1550 nm for a ring-doped erbium-doped fiber (EDF) pumped by 0.1 W, 0.2 W, and 0.5 W at 980 nm in the core. The ring thickness was sufficiently thin to make variations of the normalized modal intensity negligible over its thickness. Other parameters are listed in Tables A3 and A4 under "normal-core amplifier". For comparison, also results for EDFAs homogeneously doped throughout the core are shown, both for the "normal-core" amplifier and a "large-core" amplifier. In all cases, a higher pump power gives a higher small-signal gain and a larger extractable energy. Moreover, the fiber length was optimized for maximum small-signal gain in all cases. We see that the results are now worse, and that the benefits of ring-doping are smaller. However, performance is still superior compared to that of prior-art designs.

As an alternative, the core can be single-mode at the signal wavelength, and multi-moded for the pump. It is well-known that pump-light in higher-order modes will penetrate further into the cladding, thereby improving the pumping of the gain medium. Moreover, for so-called upconversion devices, the pump wavelength is shorter than the signal wavelength, with the favorable side-effect that the pump extends further into the ring, even if it is in the same mode as the signal.

Figure 9 shows measured results on high-energy pulse amplification for a ring-doped, core-pumped Yb^{3+}-doped fibre amplifier according to the present embodiments. Figure 9 illustrates the extractable energy ("pulse energy above cw") vs. launched pump power for a core-pumped fiber amplifier with an Yb^{3+}-doped ring. The fibre was pumped at 1000 nm, and amplified signal pulses at 1047 nm. The highest recorded extracted pulse energy (above the cw-level) of more than 60 μJ can be compared to published 10 μJ total pulse energy from large-area core amplifier (albeit at a lower pump power of 160 mW) [5], as used in the prior art for high pulse-energies. The ring-doped fibre had $\Psi_{doped} \approx 0.02\ \mu m^2$. A smaller value can allow for even larger extracted energies, as long as the pump power is large enough to create a significant gain.

The emission cross-section of erbium in glass is smaller than for many other gain media, like Nd^{3+}:glass at 1050 nm and many transition metals. It follows from Eq. 17 that the stored energy will be smaller in these media. Therefore, the improvements with ring-doping can be relatively larger than for Er^{3+}:glass.

Cladding-pumped devices

We now describe cladding-pumped ring-doped fibres for high-energy pulse amplification and generation. Because of the typically higher pump powers used with these devices and because of the separately controllable normalized pump and signal mode intensities in the doped region, the disclosed cladding-pumped devices will by far outperform any prior-art core-doped single- or few-moded waveguiding device. A typical device will be a rare-earth-activated glass fibre optically pumped by a pump beam launched into the inner cladding (cf. Fig. 3).

Figure 10 shows how the extractable energy and small-signal gain at 1550 nm depends on the position of the ring for a ring-doped EDF cladding-pumped by 1 W and 5 W at 980 nm. In particular, Figure 10 illustrates the extractable energy and small-signal gain at 1550 nm for a ring-doped EDF cladding-pumped by 1 W and 5 W at 980 nm. The ring thickness was sufficiently thin to make variations of the normalized modal intensity negligible over its thickness. Other parameters are listed in Tables A3 and A4 under "normal-

core amplifier". For comparison, also results for EDFAs homogeneously doped throughout the core are shown, both for the "normal-core" amplifier and a "large-core" amplifier. In all cases, a higher pump power gives a higher small-signal gain and a larger extractable energy. Moreover, the fiber length was optimized for maximum small-signal gain in all cases. Other parameters were the same as in Fig. 10, and are listed in Tables A3 and A4. The advantages compared to the prior-art EDFs (also shown) are substantial. The increase of the extractable energy can approach two orders of magnitude in the devices studied here.

In view of these results, we propose a ring-doped cladding-pumped optical fibre where the ring is located at a position where the mode intensity is, e.g., one or two orders of magnitude smaller than it is in its center. In order to get sufficient absorption, sensitization may be used, e.g., as in ytterbium-sensitized erbium-doped fibres.

A ring-shaped gain medium outside the core may be better pumped by a beam in the cladding. Thus, while cladding-pumping has normally been considered to facilitate launching of non-diffraction-limited sources like diode bars, we also propose to use cladding-pumped, ring-doped fibres even when high-brightness, near-diffraction-limited pumps that could be efficiently launched into the core are available. The high brightness will still be favorable because the area of the inner cladding can be small. In these devices, cladding-modes may well see a higher gain than the desired core-mode does, whereby some measure for suppressing cladding-modes would be required.

Even if only a small part of the stored energy is extracted from a ring-doped amplifier, the high stored energy may still be advantageous, since it for instance reduces the distortions of the chirped-pulse amplification with small distortions of the pulse shape.

Passively Q-switched and gain-switched lasers

In passively Q-switched lasers, energy and thereby ASE builds up in a region of gain. The ASE then transfers energy to a saturable absorber. The saturable absorber must be so that the absorption change per unit stored energy is smaller than it is in the gain region. In prior-art devices, this is achieved by using a saturable absorber with large absorption and/or stimulated emission cross-sections, compared to those of the gain medium. Ring-doped fibres

open up for Q-switched lasers where the gain section and the saturable absorber are made from the same material, e.g. an erbium-doped glass. This is possible since $E_{sat} \equiv h\nu/[\Psi_{doped}(\sigma^a + \sigma^e)]$ can be two orders of magnitude higher in the ring-doped fibre than in the core-doped one, even though the material-dependent quantities ($\sigma^a + \sigma^e$) are equal in the two different fibres.

The gain section may also be a core-doped fibre with a large area core, however, this does not work as well as a properly designed ring-doped fibre.

In a first embodiment, a ring-doped fibre is cascaded with a core-doped fibre, each of which are doped with a similar dopant with a non-negligible ground-state absorption, to form a laser cavity. A pump beam is launched into a gain section, consisting of the ring-doped fibre, thereby building up a gain and stored energy. A cw pump beam may be used, and the fibre may be cladding-pumped. The gain section generates ASE, through which energy is transferred from the gain section to a core-doped fibre constituting a saturable absorber. The pump also acts to bleach the pump-absorption in the ring-doped fibre, whereby the pump penetrates deeper into the cavity, and possibly helps in bleaching the saturable absorber. The transfer of energy from the gain section to the absorber section increases the net gain in the cavity to a point where it exceeds threshold. Then, energy is radiated from the cavity in the form of a Q-switched pulse. This substantially reduces the stored energy, and hence the gain, in the cavity, so that the ASE becomes negligible, and the pump power that penetrates to the saturable absorber becomes small. The saturable absorber then relaxes to a state that is at least partly absorbing. Thereby, the absorption in the saturable absorber has increased substantially before the gain section starts to generate ASE again, whereupon the cycle is repeated.

A second embodiment is similar to the first embodiment, except that there is provided a pump-absorber or a pump reflector between the gain-section and the saturable absorber. This substantially reduces the pumping of the saturable absorber.

A third embodiment is similar to the first or second embodiment, except that the active centra in the gain medium and the saturable absorber are different. The pump wavelength may be chosen so that it cannot bleach the saturable absorber.

Figure 11 is a view of a fiber having a saturable absorber (640) in the central part of the core (30), and a ring-shaped gain medium (620) around the absorber. In the illustrated example, the gain medium resides in the core, but it may also be placed partly or wholly in the cladding (10).

Figure 12 illustrates a semiconductor amplifier for signal amplification provides gain for a guided optical signal beam in a region where the normalized modal intensity is small. 410: cladding, 420: gain region (active layer), 430: core (index-guiding layer), 480: substrate, 490: contact layer. Also the approximate location of a signal beam is indicated (470). The refractive index of the active layer may be depresses in order to suppress gain-guiding.

Figures 13a to c illustrates devices in which unwanted, higher-order modes are suppressed by the inclusion of an absorber. 13*a*) A fiber with an amplifying ring 10 further contains an absorbing ring 510, suppressing higher-order modes. The absorption of the desired fundamental mode is small or even negligible. 13*b*) Planar waveguide with amplification of the evanescent field by a gain region 120, with an absorbing superstructure 520. Again, the absorption of the desired fundamental mode is small or even negligible. Undesired higher-order modes penetrate further into the absorber, whereby they are suppressed. 13*c*) A double-clad ring-doped optical fiber in which a signal-absorbing region 530 has been incorporated into the cladding, thereby preventing any build-up of signal light in the cladding.

Device with a distributed saturable absorber

Above, two media with different saturation characteristics were combined in a cascade. However, the two gain media may also reside side by side in the same fibre. An example of this is illustrated in Fig. 11. A fibre having a core (30) and a cladding (10) is doped with a saturable absorber (640) and a gain medium (620). Here, the saturable absorber is located in a region where the normalized modal intensity is larger than it is in the region of the gain medium. Hence, if the absorber and gain media are similar (except that the gain

medium is pumped), and the cross-section for stimulated emission of the gain medium is similar to the absorption cross-section of the absorber, the small-signal gain of the fibre can be negative or small, even though the extractable energy of the gain medium is larger than the energy required to bleach the saturable absorber. Hence, the ASE in the fibre can be suppressed, while the energy that can be extracted from the device, if for instance a signal pulse is launched into it, can be large.

In contrast to the prior art, a ring-shaped gain medium allows the active centra in the absorber and the gain media to be of the same or similar types, as long as it is possible to pump the centra in the gain medium while leaving those in the absorber medium unpumped. A particular studied embodiment consisted of an Er^{3+}-doped saturable absorber and an Yb^{3+}-sensitized Er^{3+}-doped gain medium. The Er^{3+} in the gain medium was excited indirectly (i.e., via the Yb^{3+}) by an optical pump beam launched into the fibre core. The launched pump power was 1 W at a wavelength of 1064 nm, which is a wavelength that will not excite the Er^{3+} in the saturable absorber. The fibre had a numerical aperture of 0.16, and a core diameter of 7 μm. The diameter of the saturable absorber (640) was 1 μm, while the inner and outer radii of the ring-shaped gain medium (620) were 3.4 μm and 3.5 μm, respectively. The Er^{3+}-concentration was 2.38×10^{25} m^{-3} in both the absorber and gain media, and the Yb^{3+}-concentration was 2.97×10^{26} m^{-3} in the gain medium. The absorption and emission cross-sections at the peak (wavelength 1536 nm) were both 6.8×10^{-25} m^2. Hence, the small-signal absorption at that wavelength was 2.1 dB/m in the saturable absorber, and 1.3 dB in the (unpumped) gain medium. Moreover, at 1064 nm, the cross-sections for stimulated emission and absorption of the Yb^{3+}-ions were at 2×10^{-26} m^2 and 5×10^{-28} m^2, respectively. The metastable lifetimes of the Er^{3+} and the Yb^{3+} were 10.2 ms and 1.3 ms, respectively. The energy was transferred from the Yb^{3+} to the Er^{3+} with a rate coefficient k_{tr} of 1.05×10^{-21} m^3/s [6]. The spectral characteristics of the gain and absorber region followed those for Er^{3+} and Yb^{3+} in a phosphosilicate glass. Numerical calculations, following those in [4] and [6] and using the parameters above, showed that the extractable energy in this device was approximately 0.6 mJ at 1536 nm and 1.1 mJ at 1560 nm.

In the example above, the ring-shaped gain region was thin and hence the extractable energy per unit length small. This implied that the length of the fibre became so long (several hundred meters) that background losses could become important, and the calculated energy, neglecting background losses, difficult to achieve. By placing a ring-shaped gain medium outside the core (where the normalized modal intensity is smaller), its gain can be kept constant while the stored energy in the gain medium is increased (cf. Eq. 17). Hence, the fibre can be shorter. For a cladding-pumped fibre having an inner cladding with a radius of 10 μm, a saturable absorber (640) with a radius of 0.5 μm (small-signal absorption 2.2 dB/m at 1536 nm), and a gain medium (620) with an inner radius of 4.5 μm and an outer radius of 5.5 μm (small-signal absorption 3.3 dB/m at 1536 nm), calculations gave an extractable energy of 0.8 mJ at 1536 nm and 1.4 mJ at 1560 nm, for a fibre length of 50 m. The fibre length can be further reduced by using a larger-area gain region (e.g., a thicker doped ring). The other parameters of the fibre were the same as above. A problem with this approached is that the preferred host material for a Yb^{3+}-sensitized Er^{3+}-doped gain medium (phosphosilicate glass) has a higher refractive index than the preferred cladding (fused silica). Hence, some extra measure may be needed to level the refractive index of the gain medium with that of cladding.

The calculations have also shown that ASE in the long-wavelength end of the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ emission spectrum, where the emission cross-sections become relatively larger compared to the absorption cross-section, can build up and partly bleach the absorption and compress the gain. This can be avoided by introducing an unsaturable loss at these long wavelengths. Bending the fibre provides a method for making the fibre lossy at 1600 nm, while keeping the unsaturable loss small at 1536 nm. For example, with the fibre parameters above and with a bend radius of 9 mm, the bend-loss is approximately 0.033 dB/m at 1600 nm, 0.012 dB/m at 1560 nm, and 0.0061 dB/m at 1536 nm, i.e., it is five times smaller at 1536 nm than at 1600 nm. Another alternative for an unsaturable loss at longer wavelengths is to use an unsaturable absorber in addition to the saturable absorber. For this particular transition, Tm^{3+}:glass and Tb^{3+}:glass are suitable systems for an optical fibre, as the

absorption of suitable pump wavelengths (e.g., 1064 nm or at least 1047 nm in the case of Tm^{3+}) is small, as is the absorption for a signal at 1536 nm. Yet another alternative may be to use different host media for the gain and the absorber media. A suitable host medium for the absorber makes its spectrum wider, and can thus prevent the build-up of ASE at long wavelengths.

In the example above, a pump wavelength of 1064 nm was assumed. Other wavelengths are also possible. However, the pump should not pump the Er^{3+} directly, since then also the saturable absorber will be excited. Moreover, for pumps on the short-wavelength side of the Yb^{3+} absorption peak, emission around 980 nm from the Yb^{3+} may build up in the fibre and bleach the Er^{3+}-ions in the absorber.

Even if the centra providing the gain and the saturable absorption are different, a design according to Fig. 11 can improve to prior-art devices in that the gain efficiency of the gain medium is relatively lower than it otherwise would be.

Saturable absorber

The saturation power P_{sat} of a saturable absorber is given by $P_{sat} \equiv h\nu/[\Psi_{doped}(\sigma^a + \sigma^e)\tau]$, where τ is the lifetime of a metastable state. For some devices, a medium that would otherwise be a suitable saturable absorber (e.g., because of a suitable spectral response) is inappropriate because its saturation power is too small. This may be the case for an EDF saturable absorber, with P_{sat} typically smaller than 1 mW. We here disclose that ring-doping allows Ψ_{doped} to be chosen so that a larger, predetermined value of P_{sat} can be obtained. For this application, a few-moded fibre may be acceptable for single-mode applications, as higher-order modes will experience a higher loss which may render the power in them negligible.

Signal amplifiers for reduced cross-talk

In some optical amplifiers, especially semiconductor ones, even the energy of a single signal bit (e.g., 0.1 – 100 fJ) may be non-negligible comparable to the stored energy. Then, already the amplification of a single bit extracts enough energy to reduce the gain. This leads to four-wave mixing and cross-talk in multi-wavelength amplifiers and inter-symbol

interference in single-wavelength amplifiers. This can be avoided with the higher stored energy that, for a given gain, accompanies the reduced interaction in the devices disclosed in this invention.

Figure 12 illustrates an embodiment. A semiconductor amplifier provides gain for one or several guided optical signal beams in a region where the normalized modal intensity is small. The device may be electrically pumped. The refractive index of the gain region may be depressed in order to suppress gain-guiding, since this can otherwise occur in semiconductor optical amplifiers in which the gain per unit length is large. This would lead to a large normalized modal intensity in the gain-region, thereby preventing substantial reductions of the interaction.

Suppression of unwanted modes

Often, lasing on a specific transverse mode is desired, and then normally on the fundamental mode of the core. If so, it may be necessary to suppress other, undesired, modes. Higher-order guided modes of the core extend further into the cladding and thus see a significantly higher gain than does the fundamental mode in a ring-doped device. Although we normally envisage single-moded cores as preferred designs, higher-order modes may also be present due to fabrication errors, etc. However, these modes are less strongly guided and will be more sensitive to bending. Hence, with a fibre, simply bending it can reinstate a net gain advantage for the fundamental mode.

Another alternative is to outside the gain region incorporate a region that absorbs the signal (at desired and possibly also at undesired wavelengths) but has a low loss for the pump. This absorbing region is located so that it preferentially absorbs light in undesired modes. These can be higher-order modes of the core, and also cladding-modes. See Fig. 13. Several possibilities exist for creating the absorbing region. In the case of a Yb-doped device, Pr^{3+} and Er^{3+} can be suitable such absorbers. For Nd^{3+} at 850 nm – 950 nm, Yb^{3+} can be used. For Er^{3+}, Tm^{3+} and Sm^{3+} are potential candidates, just to mention some possibilities with rare-earth doping. Sm^{3+} can also suppress unwanted 1050 nm radiation in Nd^{3+}-doped

samples. Optionally, some additional measures may be taken to quench the dopant, to prevent it from bleaching.

The reader's attention is directed to all papers and documents which are filed concurrently with or previous to this specification in connection with this application and which are open to public inspection with this specification, and the contents of all such papers and documents are incorporated herein by reference.

All of the features disclosed in this specification (including any accompanying claims, abstract, and drawings), and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at least some of such features are mutually exclusive.

Each feature disclosed in this specification (including any accompanying claims, abstract, and drawings), may be replaced by alternative features serving the same, equivalent, or similar purpose, unless expressly stated otherwise. Thus, unless expressly stated otherwise, each feature disclosed is one example only of a generic series of equivalent or similar features.

The invention is not restricted to the details of the foregoing embodiments. The invention extends to any novel one, or any novel combination, of the steps of any method or process so disclosed.

In the embodiments described above a ring-shaped (generally cylindrical) doped region has been used. However, the doped region does not of course have to be rotationally symmetric, nor evenly distributed along the length of the fibre or waveguide.

Tables

Active medium	*Wavelength / nm*	*Absorption cross-section / 10^{-25} m^2*	*Emission cross-section / 10^{-25} m^2*	*Remark*
Nd^{3+}:glass	800	20	0	Pump to $^4F_{5/2}$.
Nd^{3+}:glass	870	10	10	
Nd^{3+}:glass	1050	0	30	Unwanted wavelength
Yb^{3+}:glass	912	8.25	0.275	Pump
Yb^{3+}:glass	975	25.85	25.85	
Yb^{3+}:glass	980	6.76	8.57	
Yb^{3+}:glass	985	1.77	2.97	
Yb^{3+}:glass	1030	0.45	6.3	Unwanted wavelength
Er^{3+}:glass	980	2	0	Pump to $^4I_{11/2}$
Er^{3+}:glass	1531	5	5	
Er^{3+}:glass	1550	2.4	3.8	
Er^{3+}:glass	1564	1.6	3	Unwanted wavelength

Table A1. Cross-sections for absorption and stimulated emission used in some numerical examples.

Quantity	*Symbol*	*Value*
Numerical aperture	NA	0.1
Core diameter		7 μm
Cut-off wavelength	λ_c	915 nm
Doped area	A_{doped}	38.5 μm^2
Yb concentration	$[Yb^{3+}]$	2.7×10^{25} m^{-3}
Signal overlap with core	Γ_{core}	0.796
Area of inner cladding	A_{pump}	3080 μm^2
Pump overlap with core	$\Gamma_{p,\ core}$	1/80
Effective area ratio for core-doped device	$r_{effective}$	63.7
Small-signal pump-absorption	α_p^{ss}	1.21 dB/m
Metastable lifetime	τ	0.76 ms
Background loss	–	0 dB/m
Reflectivity, pump launch end	–	99.9% at desired wavelength, 0 elsewhere
Reflectivity at other end	–	Either 3.5% broadband, or 50% at desired wavelength and 0% elsewhere

Table A2. Values used in detailed Yb-calculations. Other parameters as in Table A1.

Quantity	*Symbol*	*Normal-core amplifier*	*Large-core amplifier*
Core diameter		5 μm	11 μm
Numerical aperture	NA	0.171	0.100
Cut-off wavelength	λ_c	1118 nm	1437 nm
Signal overlap with core	Γ_{core}	0.651	0.795
Area of inner cladding for cladding-pumping	A_{pump}	1571 μm^2	1571 μm^2
Pump overlap with core for cladding-pumping	$\Gamma_{p,\ core}$	1/80	1/16.5
Effective area ratio for core-doped device	–	52.1	13.1
Background loss	–	0 dB/m	0 dB/m

Table A3. Geometrical and dopant parameters for energy-storage EDFAs.

Quantity	*Symbol*	*Value*
Metastable lifetime	τ	10.9 ms
Absorption cross-section at 1480 nm	s^{a}_{1480}	1.87×10^{-25} m^2
Emission cross-section at 1480 nm	s^{e}_{1480}	0.75×10^{-25} m^2
Absorption cross-section at 980 nm	s^{a}_{980}	2×10^{-25} m^2
Absorption cross-section at 1550 nm	s^{a}_{1550}	2.45×10^{-25} m^2
Emission cross-section at 1550 nm	s^{e}_{1550}	3.83×10^{-25} m^2
Pump intensity required at 1480 nm to invert 35.7% of the population	I_{sat}	0.0470 mW/μm^2
Pump intensity required at 980 nm to invert half the population	I_{sat}	0.0930 mW/μm^2

Table A4. Spectroscopic parameters for energy-storage EDFAs.

Publication References

1. C. R. Giles et al, "Modeling erbium-doped fibre amplifiers", J. Lightwave Technol. **9**, 271-83, (1991)
2. R. Paschotta et al, "Lifetime quenching in Yb doped fibres", submitted to Opt. Commun.
3. B. Pedersen et al, "The design of erbium-doped fibre amplifiers", J. Lightwave Technol. 9, 1105-1112 (1991)
4. J. Nilsson et al, "Modelling and optimisation of low repetition-rate high-energy oulse amplification in cw-pumped erbium-doped fibre amplifiers", Opt. Lett. **18**, 2099-2101 (1993)
5. D.T. Walton et al, "Broad-bandwidth pulse amplification to the 10-μJ level in an ytterbium-doped germanosilicate fibre", Opt. Lett. 21, 1061-1063 (1996)
6. J. Nilsson et al, "Modeling and optimization of short Yb^{3+}-sensitized Er^{3+}-doped fibre amplifiers", IEEE Photon. Technol. Lett. 6, 383-385 (1994).

CLAIMS

1. An optical waveguide comprising: a light-guiding core and a cladding surrounding the core, in which a region of the cladding is formed of an amplifying medium.

2. A waveguide according to claim 1, in which substantially all of the core is formed of a non-amplifying medium.

3. A waveguide according to claim 1 or claim 2, the waveguide being an optical fibre.

4. A waveguide according to claim 3, the waveguide being a single-mode optical fibre.

5. An optical waveguide in which an amplifying medium is provided in a region of the waveguide where the interaction of an opticla signal passing through the device and the amplifying medium is relatively weak.

6. A waveguide according to any one of the preceding claims, in which a medium providing saturable absorption is disposed in a region where the normalized intensity of the signal beam is large.

7. A waveguide according to claim 6, in which the saturable absorber is disposed in the waveguide core.

8. An optical amplifier comprising a waveguide according to any one of the preceding claims and means for pumping the amplifying merdium in the waveguide.

9. An amplifier according to claim 8, comprising means for inhibiting a pump beam from reaching the saturable absorber.

10. An amplifier according to claim 8, in which the saturable absorber may be pumped by a pump-beam, thereby creating a gain-switched device.

11. A laser or other light source comprising an amplifier according to any one of claims 8 to 10 and means for promoting light generation by the amplifier.

12. A laser or light source according to claim 11, in which the promoting means comprises one or more reflectors.

13. An amplifier, laser, or superfluorescent source, in which an amplifying medium longitudinally distributed along a waveguide is used with a saturable absorber, also longitudinally distributed along the waveguide.

14. A waveguide, amplifier or laser according to any of the preceding claims, in which higher-order modes are made lossy by deliberately bending the waveguide.

15. A waveguide, laser or optical amplifier according to any of the preceding claims, in which higher-order signal-modes are suppressed by the introduction of a signal-absorbing medium in a region where the normalized intensity of the fundamental, desired, mode is weak compared to those of unwanted modes.

Fig. 1

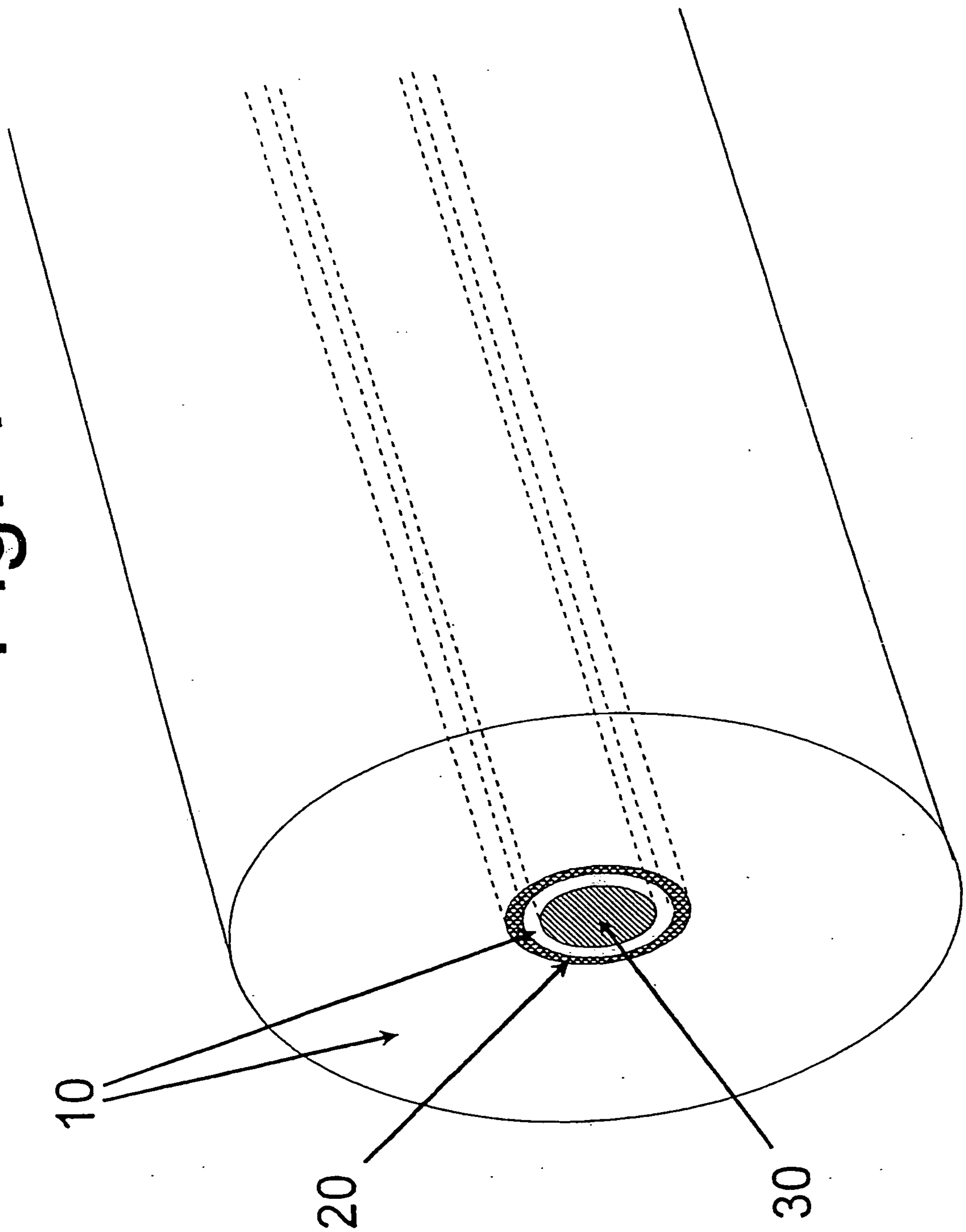


Fig. 2

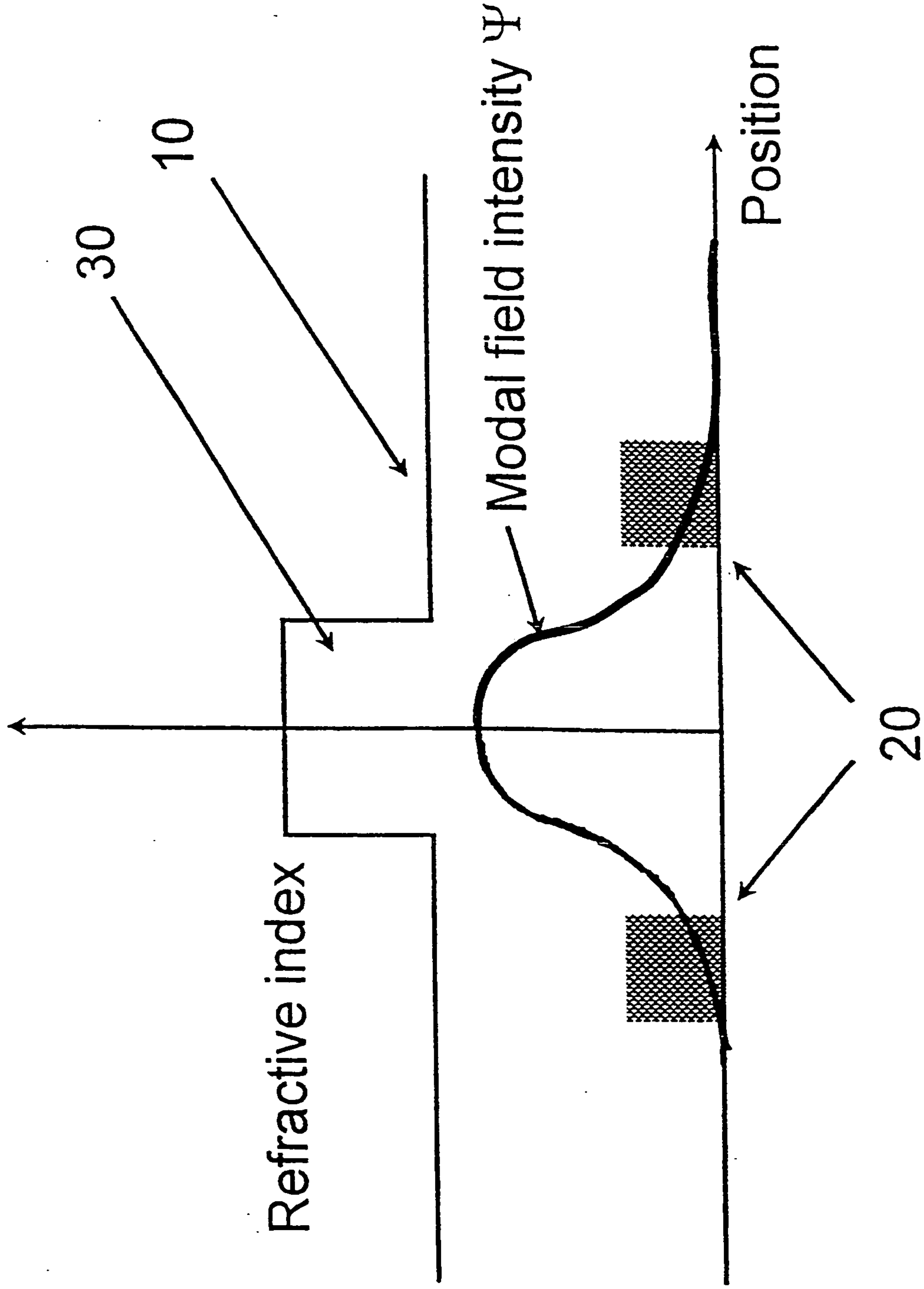


Fig 3

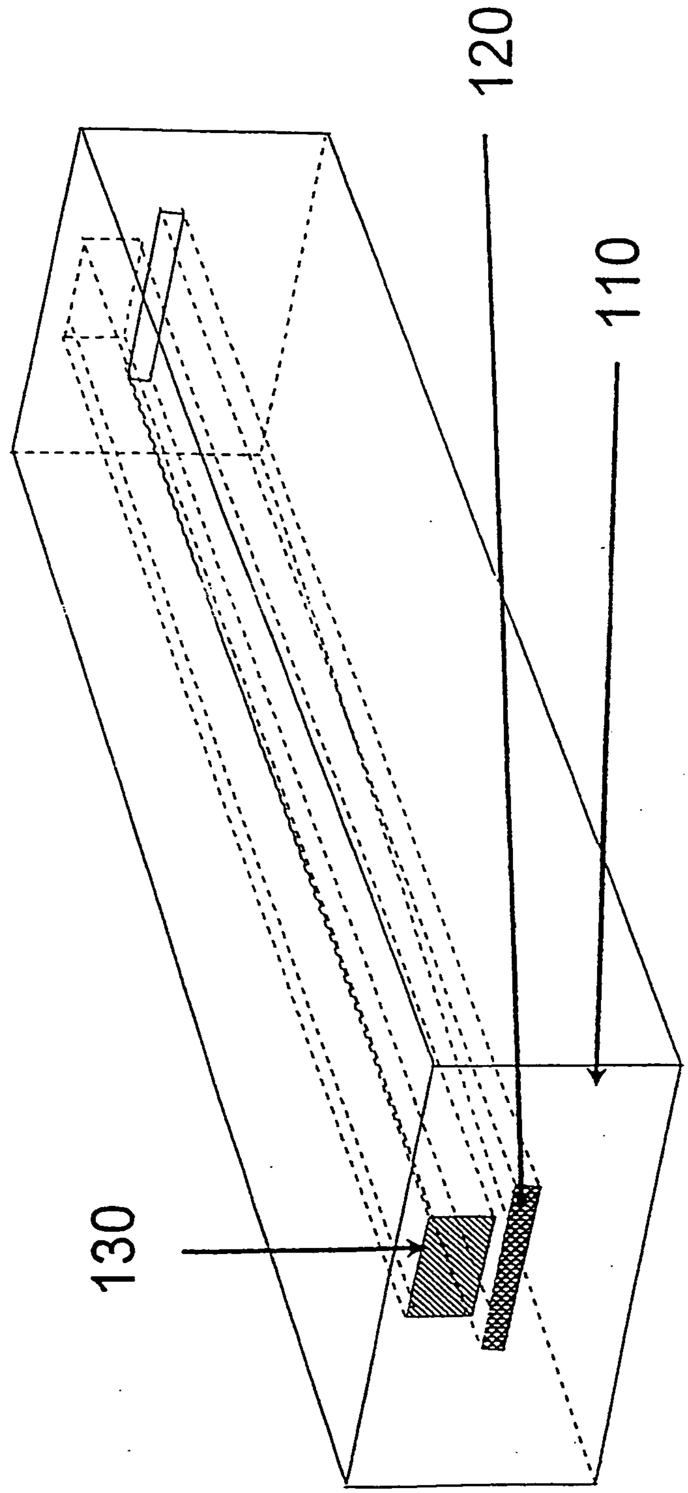


Fig. 4

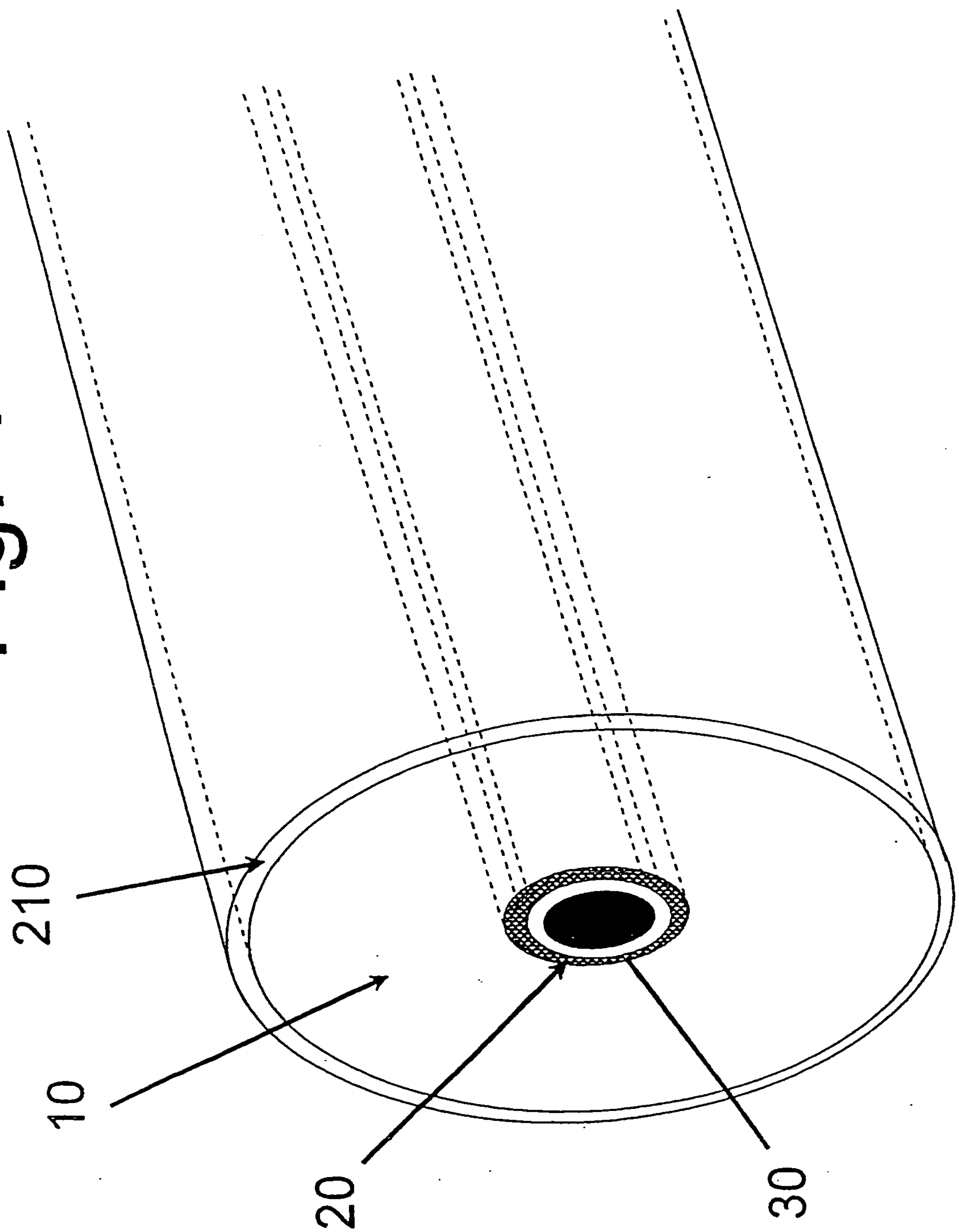


Fig. 5a

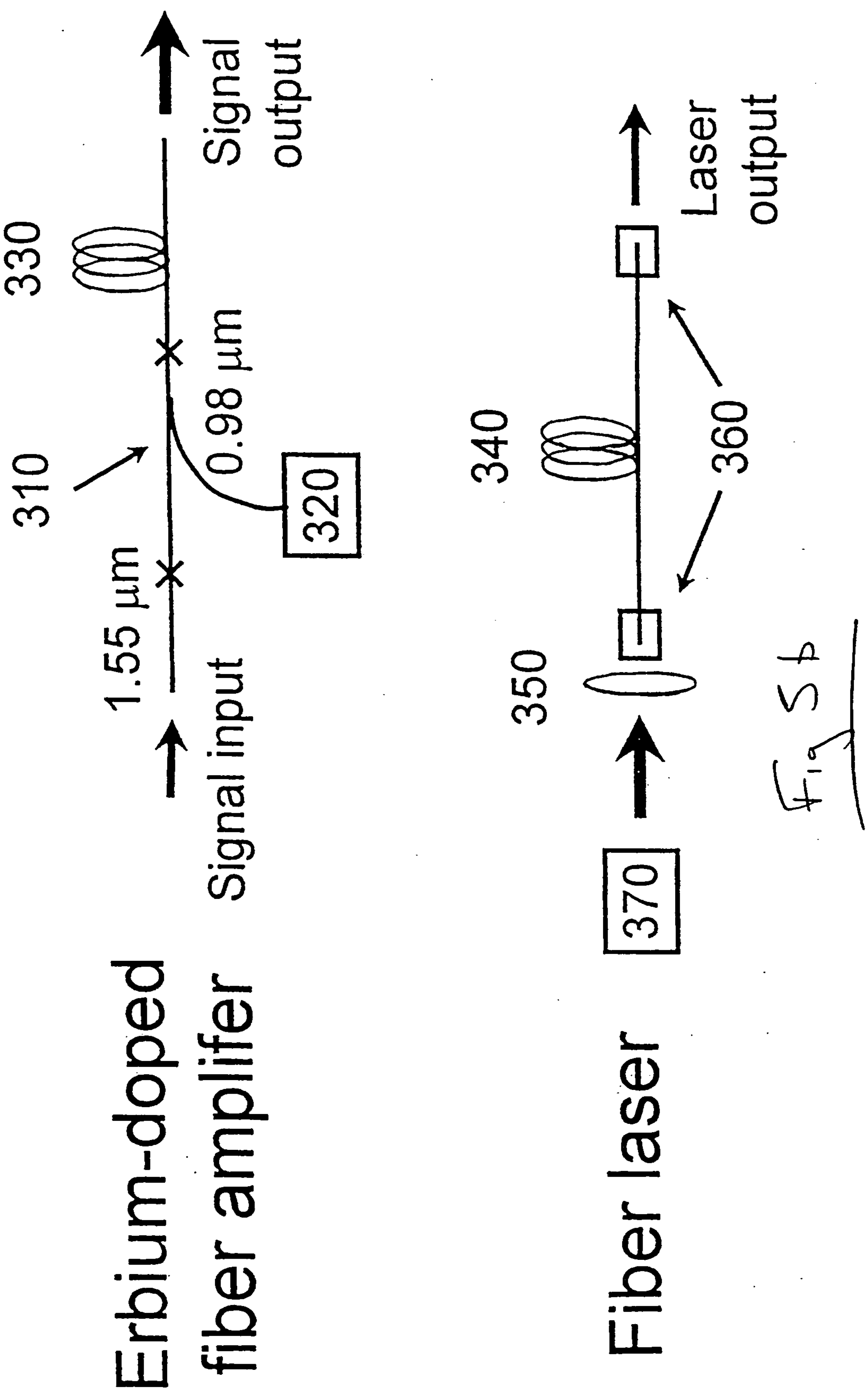

Erbium-doped fiber amplifier
Signal input
1.55 μm
310
320
0.98 μm
330
Signal output
Fiber laser
370
350
340
360
Laser output

Fig 5b

Fig. 6

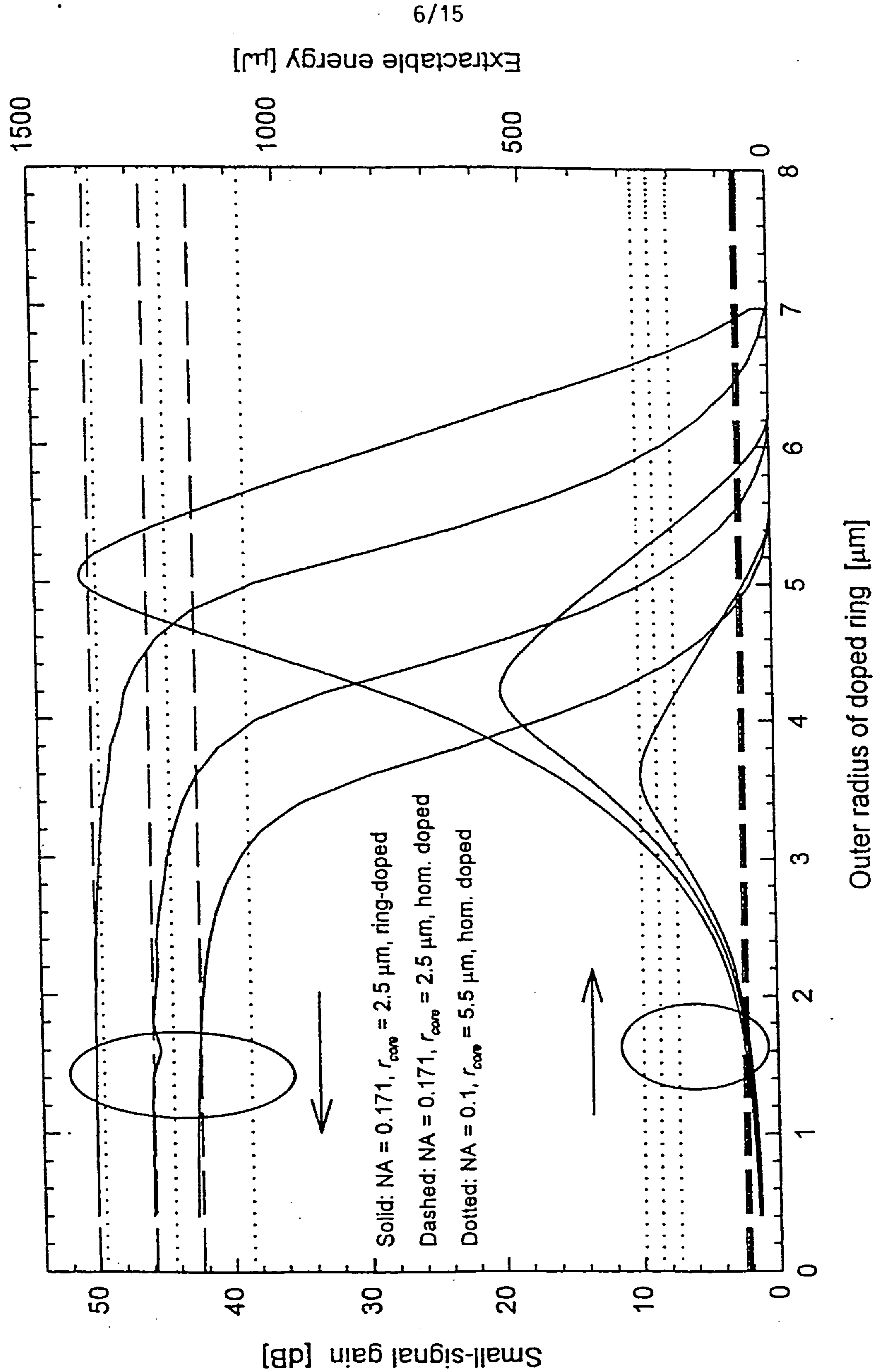

Extractable energy [μJ]
1500
1000
500
0
Small-signal gain [dB]
50
40
30
20
10
0
Outer radius of doped ring [μm]
0
1
2
3
4
5
6
7
8
Solid: NA = 0.171, r_{core} = 2.5 μm, ring-doped
Dashed: NA = 0.171, r_{core} = 2.5 μm, hom. doped
Dotted: NA = 0.1, r_{core} = 5.5 μm, hom. doped

Fig. 7

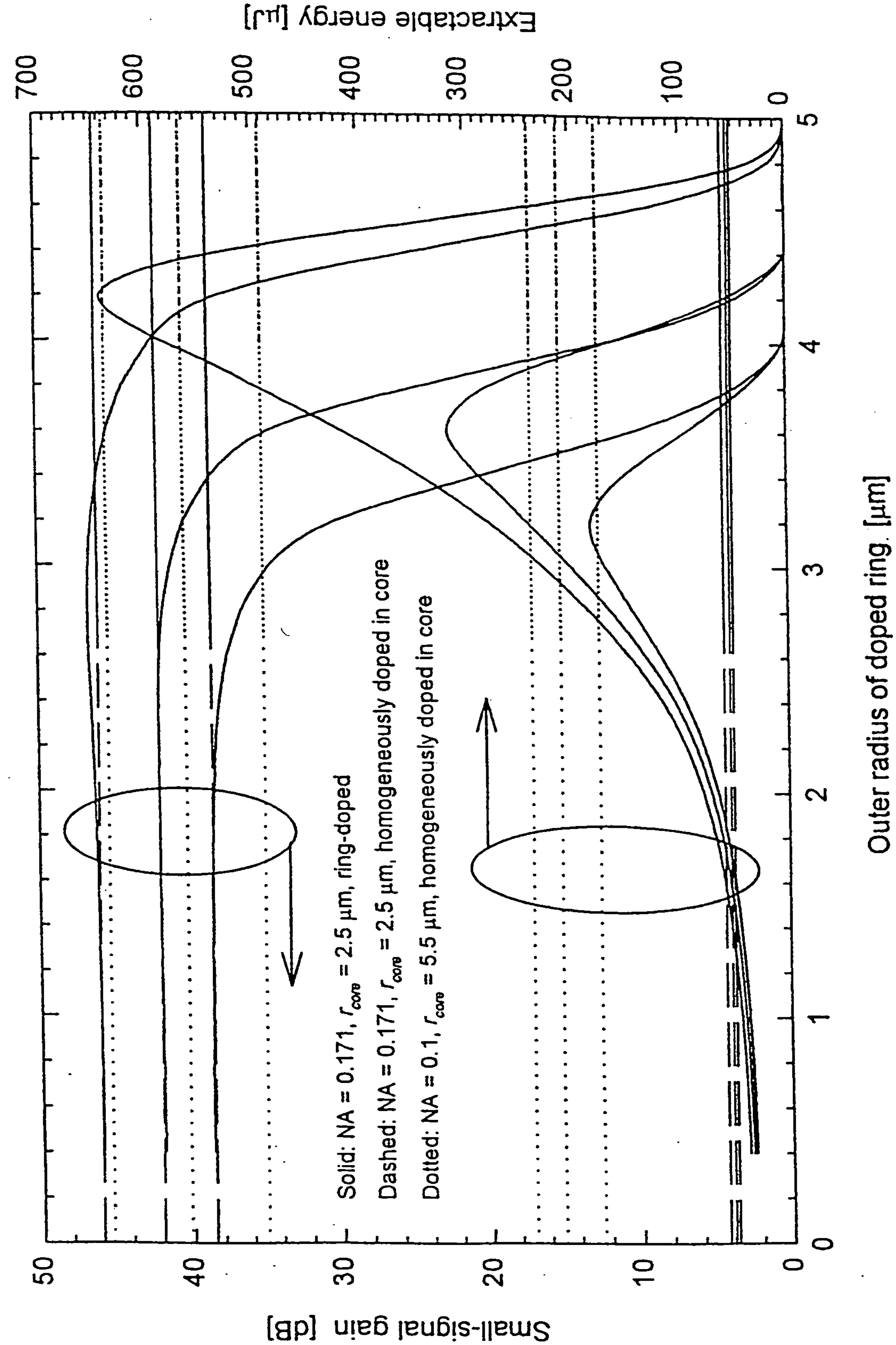
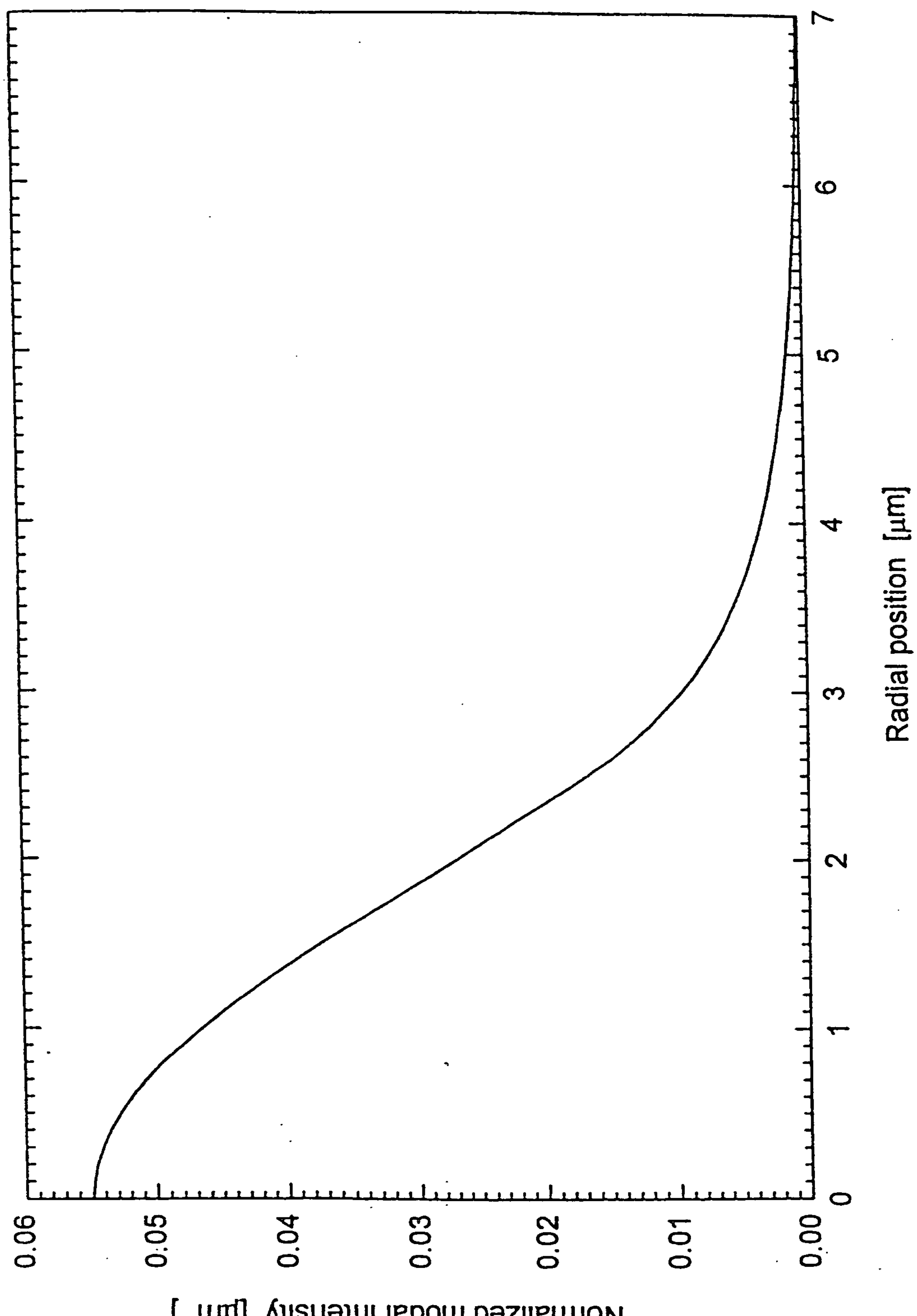

Extractable energy [µJ]
700
600
500
400
300
200
100
0
Small-signal gain [dB]
50
40
30
20
10
0
Outer radius of doped ring [µm]
0
1
2
3
4
5
Solid: NA = 0.171, r_{core} = 2.5 µm, ring-doped
Dashed: NA = 0.171, r_{core} = 2.5 µm, homogeneously doped in core
Dotted: NA = 0.1, r_{core} = 5.5 µm, homogeneously doped in core

Fig. 8


Normalized modal intensity [µm^{-2}]
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0
1
2
3
4
5
6
7
Radial position [µm]

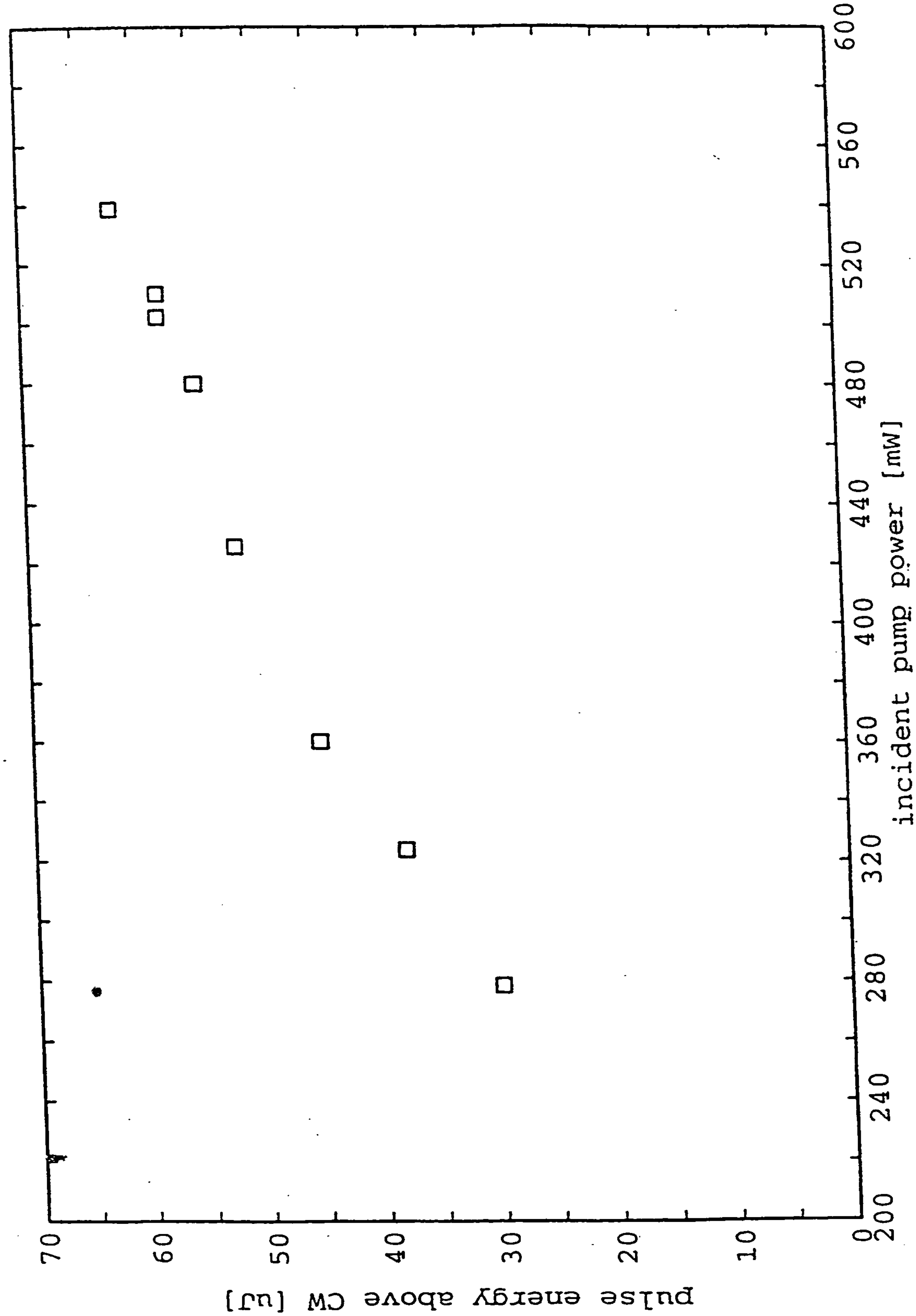
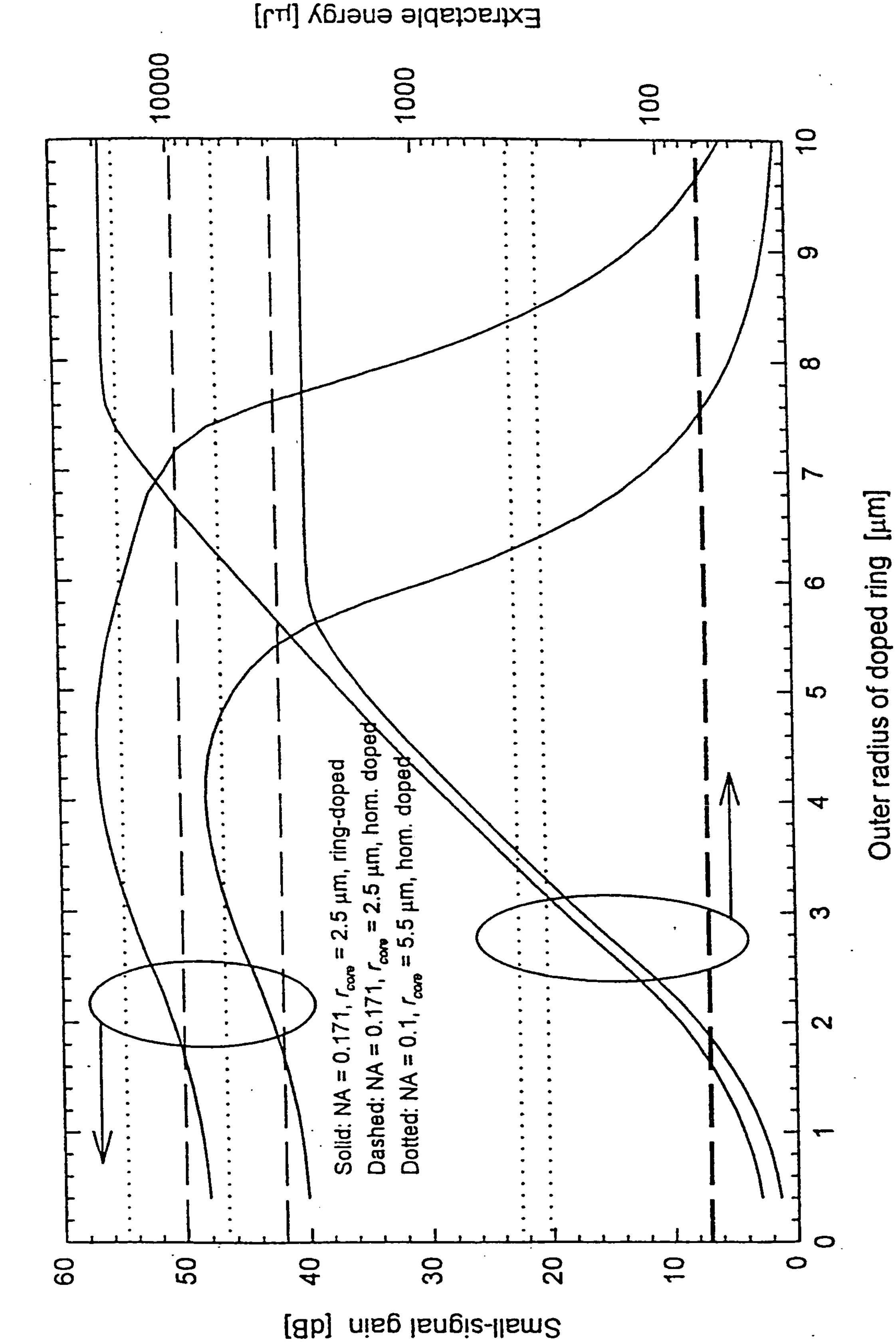

pulse energy above CW [uJ]
incident pump power [mW]
0
10
20
30
40
50
60
70
200
240
280
320
360
400
440
480
520
560
600

Fig. 9

Fig. 10


Extractable energy [µJ]
10000
1000
100
Small-signal gain [dB]
60
50
40
30
20
10
0
Outer radius of doped ring [µm]
0
1
2
3
4
5
6
7
8
9
10
Solid: NA = 0.171, r_{core} = 2.5 µm, ring-doped
Dashed: NA = 0.171, r_{core} = 2.5 µm, hom. doped
Dotted: NA = 0.1, r_{core} = 5.5 µm, hom. doped

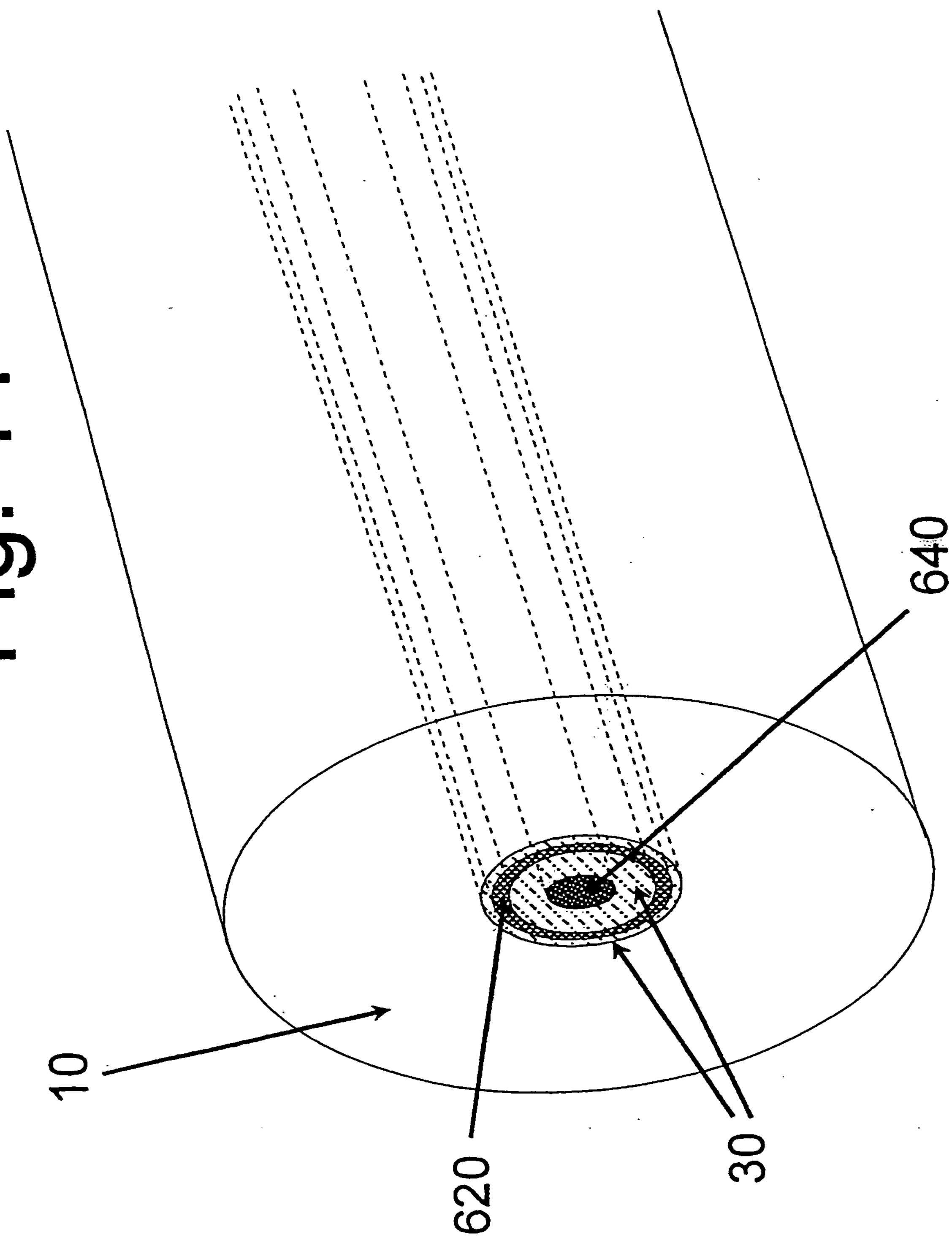


Fig. 11

Fig. 12

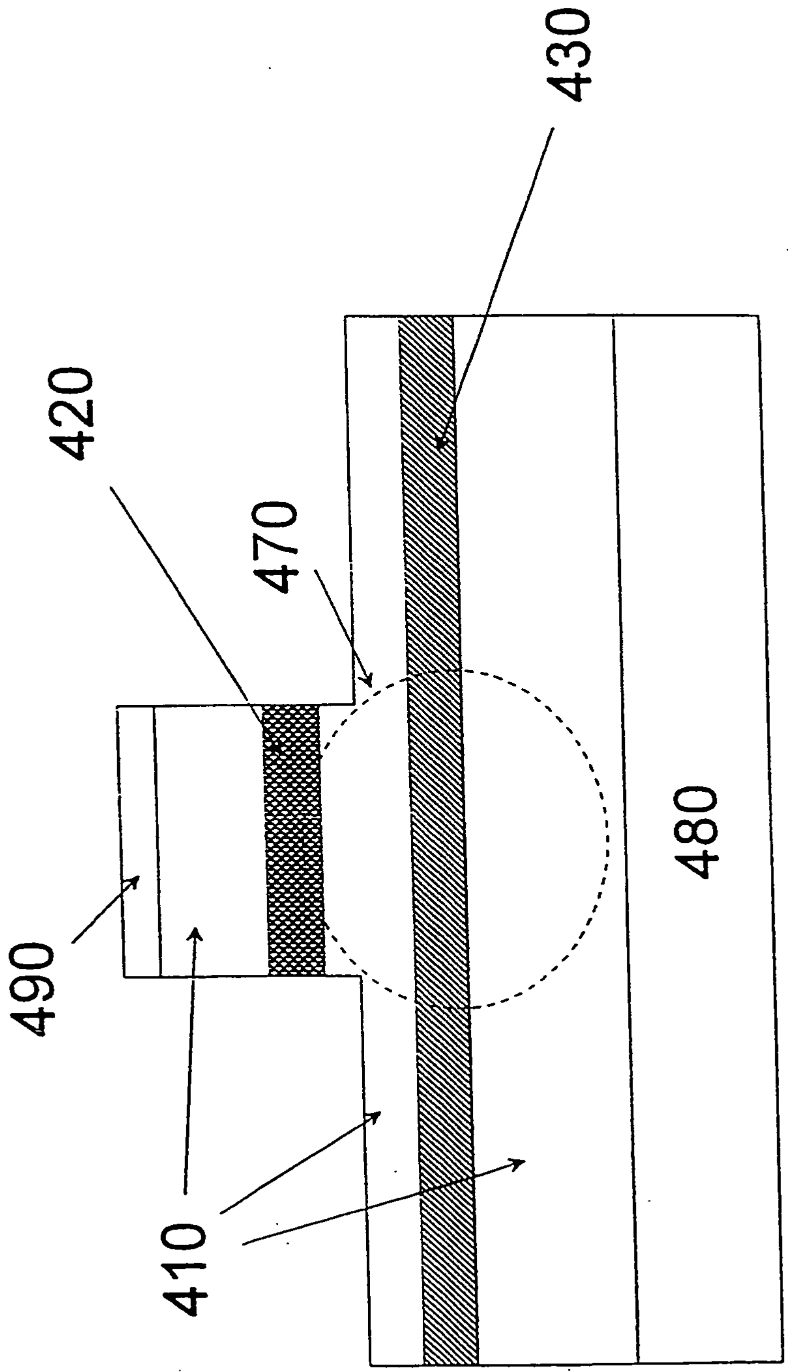


Fig. 13a

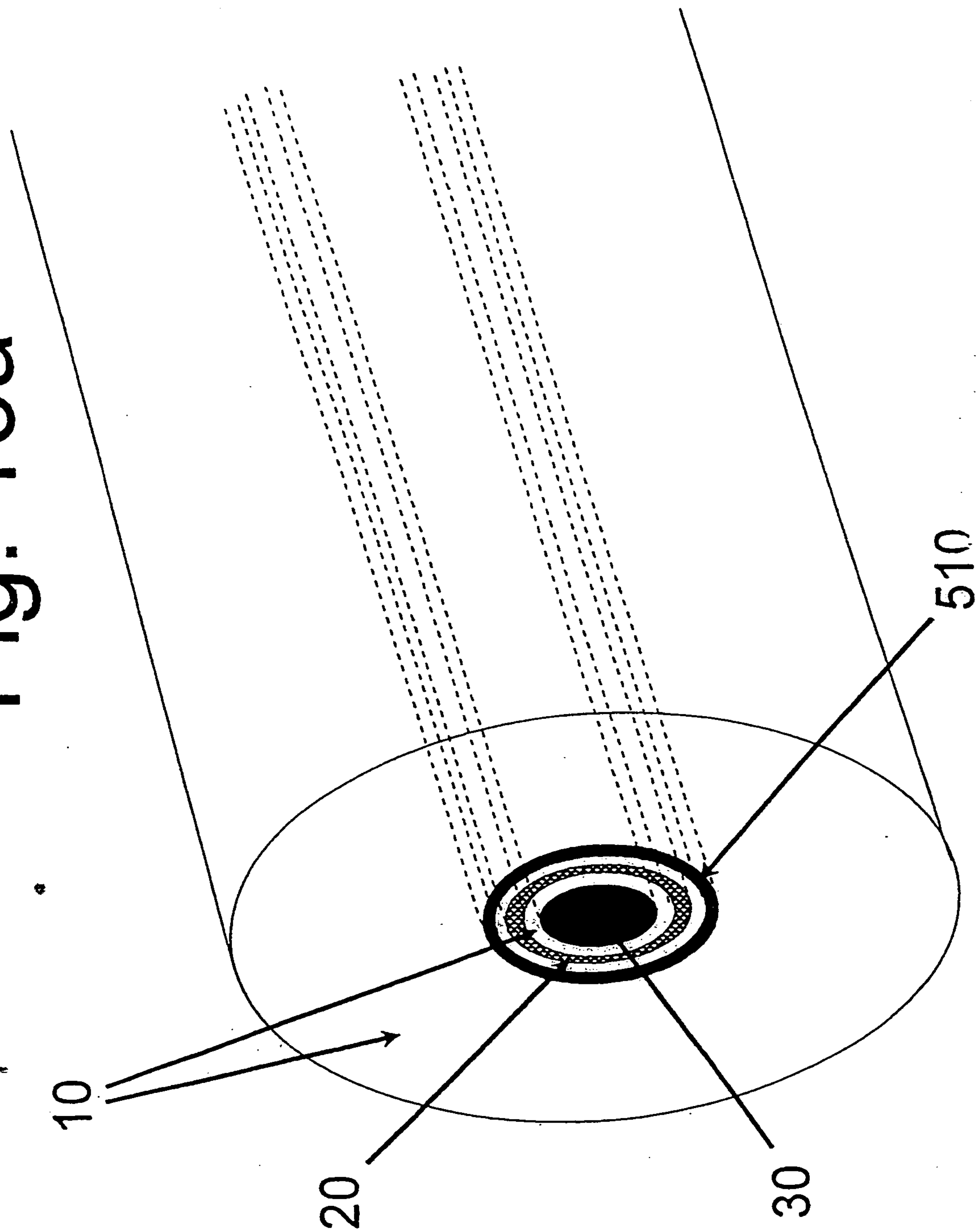


Fig. 13b

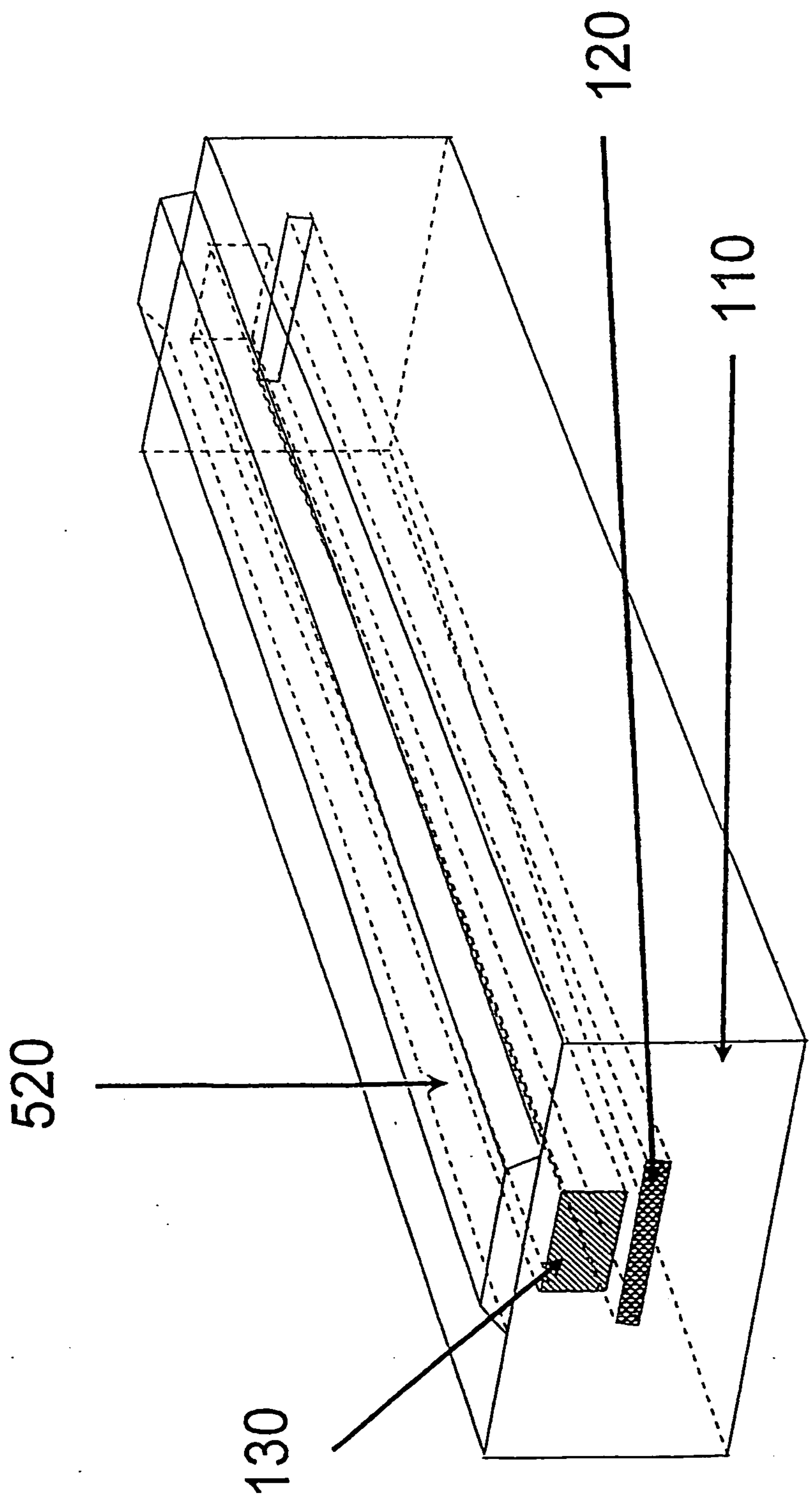
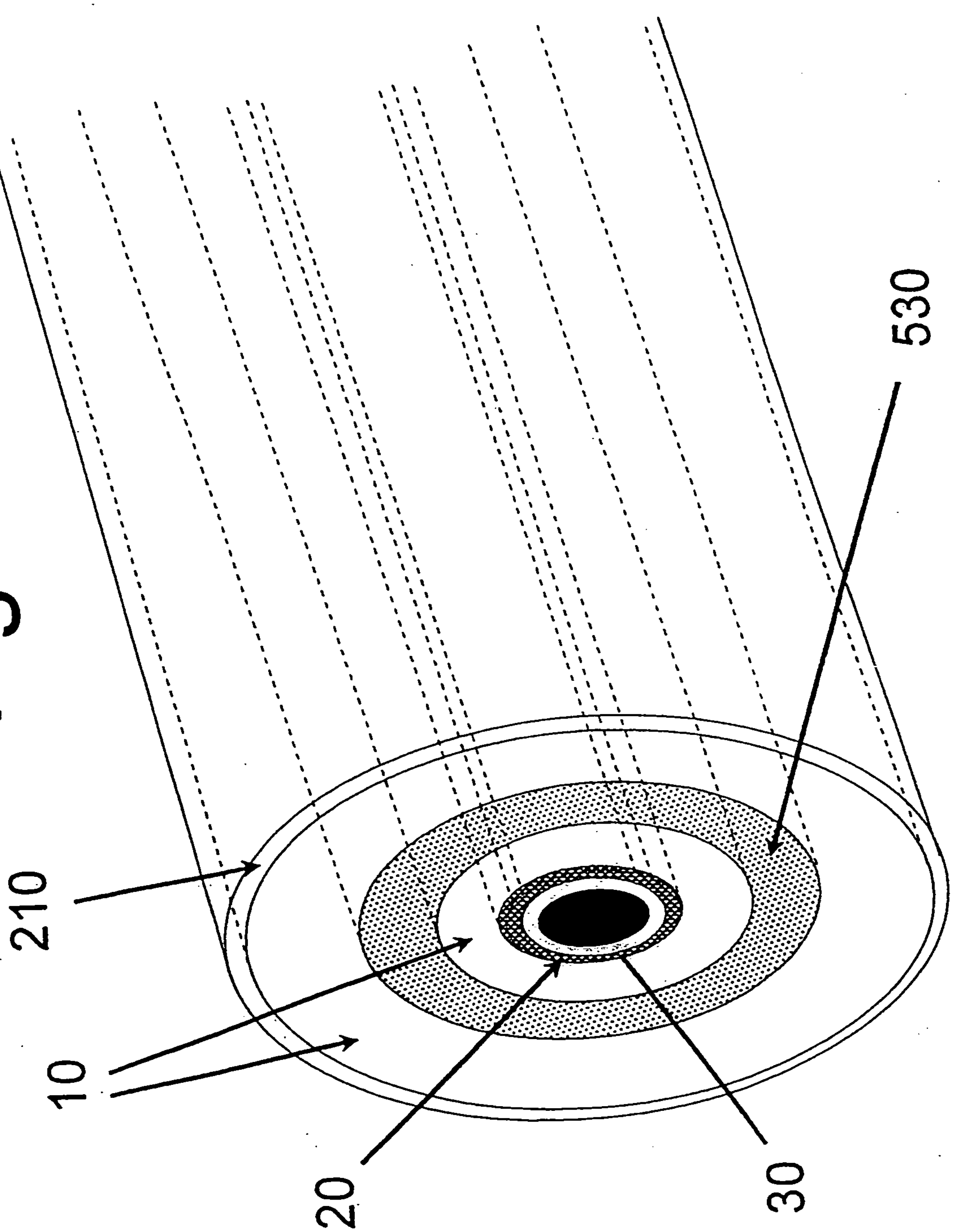


Fig. 13C



INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 97/03353

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01S3/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 5 469 292 A (BJARKLEV ANDERS O ET AL) 21 November 1995 see column 2, line 5 - line 19 see column 3, line 37 - line 46 ---	1-5,8, 11,12 6,7,9, 10,14,15
X	GLAS P ET AL: "A NOVEL DESIGN FOR A HIGH BRIGHTNESS DIODE PUMPED FIBER LASER SOURCE" OPTICS COMMUNICATIONS, vol. 122, no. 4/06, 1 January 1996, pages 163-168, XP000548782 see abstract; figure 1 ---	1-4

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

2

Date of the actual completion of the international search	Date of mailing of the international search report
25 March 1998	06/04/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Galanti, M

Form PCT/ISA/210 (second sheet) (July 1992)

Int. tional Application No
PCT/GB 97/03353

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PETROV M P ET AL: "Gain saturation in three- and four-level fiber amplifiers" OPTICS COMMUNICATIONS, 15 JULY 1994, NETHERLANDS, vol. 109, no. 5-6, ISSN 0030-4018, pages 499-506, XP002060162 see page 503, right-hand column, line 19 - line 22	1-4
P,X	NILSSON J ET AL: "Yb/sup 3+/-ring-doped fiber for high-energy pulse amplification" OPTICS LETTERS, 15 JULY 1997, OPT. SOC. AMERICA, USA, vol. 22, no. 14, ISSN 0146-9592, pages 1092-1094, XP000699832 see figure 1	1-5
X	EP 0 527 265 A (CORNING INC) 17 February 1993	13
Y	see abstract	6,7,9
X	EP 0 519 648 A (AMERICAN TELEPHONE & TELEGRAPH) 23 December 1992	13
Y	see abstract	10
Y	KIM H S ET AL: "LONGITUDINAL MODE CONTROL IN FEW-MODE ERBIUM-DOPED FIBER LASERS" OPTICS LETTERS, vol. 21, no. 15, 1 August 1996, pages 1144-1146, XP000622104 see abstract	15
Y	EP 0 442 553 A (PIRELLI CAVI SPA) 21 August 1991 see abstract	14

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 97/03353

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5469292 A	21-11-95	DK 137691 A	20-01-93
		AU 2386392 A	23-02-93
		DE 69214453 D	14-11-96
		WO 9302492 A	04-02-93
		EP 0595957 A	11-05-94
		JP 7504298 T	11-05-95
EP 0527265 A	17-02-93	US 5131069 A	14-07-92
		AU 638179 B	17-06-93
		AU 8833891 A	25-02-93
		CA 2057535 A	13-02-93
		DE 69109672 D	14-06-95
		DE 69109672 T	08-02-96
		HK 178895 A	01-12-95
		JP 5048178 A	26-02-93
EP 0519648 A	23-12-92	US 5128800 A	07-07-92
		CA 2064424 A,C	20-12-92
		DE 69202404 D	14-06-95
		DE 69202404 T	25-01-96
		JP 2555247 B	20-11-96
		JP 6224505 A	12-08-94
EP 0442553 A	21-08-91	IT 1237980 B	19-06-93
		AT 119690 T	15-03-95
		AU 642698 B	28-10-93
		AU 7081891 A	15-08-91
		CA 2034797 A,C	13-08-91
		CN 1054137 A,B	28-08-91
		CS 9100300 A	15-09-91
		DE 69107872 D	13-04-95
		DE 69107872 T	07-09-95
		ES 2072523 T	16-07-95
		FI 910649 A	13-08-91
		HK 2596 A	12-01-96
		IE 67357 B	20-03-96
		JP 4298724 A	22-10-92
		PL 164373 B	29-07-94
		PT 96736 A	31-12-92
		RU 2086062 C	27-07-97

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 97/03353

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0442553 A		US 5161050 A	03-11-92

CORRECTED VERSION*

PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : H01S 3/06	A1	(11) International Publication Number: WO 98/25326 (43) International Publication Date: 11 June 1998 (11.06.98)

(21) International Application Number: PCT/GB97/03353

(22) International Filing Date: 4 December 1997 (04.12.97)

(30) Priority Data:
9625231.7 4 December 1996 (04.12.96) GB

(71) Applicant (*for all designated States except US*): UNIVERSITY OF SOUTHAMPTON [GB/GB]; Highfield, Southampton, Hampshire SO17 1BJ (GB).

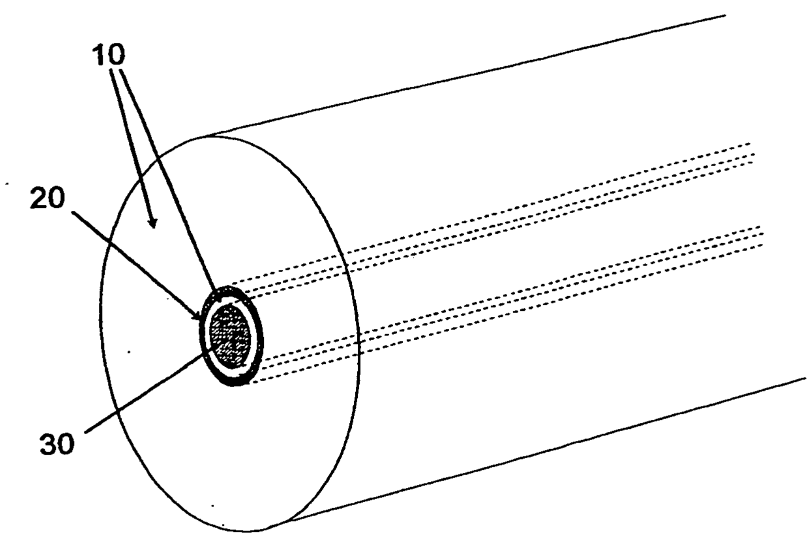
(72) Inventors; and
(75) Inventors/Applicants (*for US only*): NILSON, Johan [SE/KR]; Samsung 1–cha Apt. 2–701, Kyungki–do, Paldal–gu, Maetan–4 dong, Suwon 442–374 (KR). HANNA, David, Colin [GB/GB]; 246 Hill Lane, Shirley, Southampton, Hampshire SO15 7PH (GB). MINELLY, John, Douglas [GB/GB]; 21 Tremona Court, Tremona Road, Shirley, Southampton, Hampshire SO16 6TH (GB). PASCHOTTA, Ruediger, Eberhard [DE/CH]; Benedikt–Fontana–Weg 17, CH–8049 Zürich (CH).

(74)Agent: D. Young & Co., 21 New Fetter Lane, London EC4A 1DA (GB).

(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ARIPO patent (GH, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: OPTICAL AMPLIFIER AND LIGHT SOURCE



(57) Abstract

We disclose single– or few–moded waveguiding cladding–pumped lasers, superfluorescent sources, and amplifiers, as well as lasers, including those for high–energy pulses, in which the interaction between the waveguided light and a gain medium is substantially reduced. This leads to decreased losses of guided desired light as well as to decreased losses through emission of undesired light, compared to devices of the prior art. Furthermore, also cross–talk and inter–symbol interference in semiconductor amplifiers can be reduced. We also disclose devices with a predetermined saturation power. As a preferred embodiment of the invention, we disclose a single (transverse) mode optical fibre laser or amplifier in which the active medium (providing gain or saturable absorption) is of the fibre's cross section where the intensity of the signal light is substantially reduced compared to its peak value. The fibre may be cladding–pumped.

*(Referred to in PCT Gazette No. 34/1998, Section II)

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece			TR	Turkey
BG	Bulgaria	HU	Hungary	ML	Mali	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MN	Mongolia	UA	Ukraine
BR	Brazil	IL	Israel	MR	Mauritania	UG	Uganda
BY	Belarus	IS	Iceland	MW	Malawi	US	United States of America
CA	Canada	IT	Italy	MX	Mexico	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NE	Niger	VN	Viet Nam
CG	Congo	KE	Kenya	NL	Netherlands	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NO	Norway	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	NZ	New Zealand		
CM	Cameroon			PL	Poland		
CN	China	KR	Republic of Korea	PT	Portugal		
CU	Cuba	KZ	Kazakstan	RO	Romania		
CZ	Czech Republic	LC	Saint Lucia	RU	Russian Federation		
DE	Germany	LI	Liechtenstein	SD	Sudan		
DK	Denmark	LK	Sri Lanka	SE	Sweden		
EE	Estonia	LR	Liberia	SG	Singapore		